MANAGING FLOW, SEDIMENT AND HYDROPOWER IN THE MEKONG RIVER BASIN

A Dissertation

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

by

Thomas Bernard Wild

August 2014

MANAGING FLOW, SEDIMENT AND HYDROPOWER IN THE MEKONG RIVER BASIN

Thomas Bernard Wild, Ph. D.

Cornell University 2014

The Mekong River basin in Southeast Asia is one of the world's most productive and diverse ecosystems. Originating from the Tibetan Plateau, for much of its history the river flowed freely, draining parts of China, Myanmar, Thailand, Lao PDR, Cambodia and Vietnam on its way to the South China Sea. Currently, dams are being constructed at a rapid pace in China on the upper portion of the river, and on the river's tributaries throughout the basin, with plans to build dams on the lower mainstream Mekong River as well. These dams could trap a significant fraction of the 160 million metric tons of sediment annually transported by the river, thereby preventing the sediment from maintaining the basin's geomorphologic features, and from transporting the nutrients that support ecosystem productivity. This dissertation describes the development of a methodology to (1) identify reservoirs that could significantly alter the natural sediment regime, (2) assess alternative dam siting, design and operating policies that could improve sediment passage compared to current plans, and (3) quantify the losses in hydropower production that may be necessary to achieve improved sediment passage. To permit such evaluations, a sediment simulation model, *SedSim*, was developed in partnership with various water resources and energy ministries in Cambodia, Lao PDR and Vietnam. The model implements a daily time-step mass-balance simulation of flow and sediment to predict the spatial and temporal accumulation, depletion, and distribution of sediment in river reaches and in reservoirs under different flow and sediment management policies. This methodology is applied to dams on the transboundary Sre Pok, Se San and Se Kong tributaries of the Mekong, as well as

on the mainstream Mekong River. Results from applying this methodology suggest that various changes to the siting, design and operating policies of reservoirs can significantly improve sediment passage through and around reservoirs, but that in many cases, significant sacrifices in energy production will be required to achieve the improved sediment passage.

BIOGRAPHICAL SKETCH

Thomas Wild was born in Takoma Park, Maryland in 1985. He graduated Cum Laude with a B.S. in Civil Engineering from the University of Maryland, College Park in December 2007. In Fall 2008 he joined the Environmental and Water Resources Systems (EWRS) group in the School of Civil and Environmental Engineering at Cornell University.

To Mary, Dick, Sarah and Clark

ACKNOWLEDGMENTS

I would first like to thank the Chair of my Special Committee, Professor Pete Loucks, for the tremendous support and guidance he has offered me since the beginning of my graduate school career in 2008. Not only has the work that appears in this dissertation benefited from Pete's guidance and wisdom, but I have benefitted personally from Pete's positive influence as well. I would also like to extend my thanks to special committee members Professor Jon Conrad and Professor Jim Bisogni, for their valuable academic and research guidance. Next, I extend my gratitude to Matt Kondolf and Zan Rubin for helpful discussions on sediment and for providing sediment load predictions; and to Tom Cochrane, Thanapon Piman and Mauricio Arias for help generating 3S basins maps and simulating 3S basins flows. Additionally, I wish to thank George Annandale for guidance in improving the modeling tools and sediment management alternatives that form the basis of this dissertation. Finally, I wish to thank the Mekong River Commission for providing data and advice throughout this work, including reservoir and dam characteristics data (*MRC* 2012) and streamflow data (*MRC*, 2011a). This work was performed in conjunction with the Natural Heritage Institute (NHI), and was partially funded by a grant from the U.S. Agency for International Development (USAID), Cooperative Agreement No. AID-486-A-11-00002.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1 Motivation

Worldwide, more than 50% of sediment flux in regulated river basins is being trapped in reservoirs or other artificial impoundments [*Vörösmarty et al.*, 2003]. Reservoir sediment trapping can have three critical impacts on river basins over time: (1) alteration of the morphology of the river, which affects physical features and habitats [*Grant*, 2012; *Power et al.*, 1996]; (2) reduction of nutrients (particularly phosphorus) and organic matter that are transported primarily by clay and silt [*Baran and Guerin*, 2012]; and (3) reduction of reservoir storage capacity and hence energy production and reliability, as well as other benefits dams provide [*Mahmood*, 1987; *White*, 2001]. Until very recently, the Mekong River basin was one of the only remaining large river basins in the world not contributing to this problem.

For most of its history, the Mekong flowed freely from the Tibetan plateau through China (where it is called the Lancang Jiang), and then through the Lower Mekong Basin (LMB), draining parts of Myanmar, Thailand, Lao PDR, Cambodia, and Vietnam on its way to the South China Sea. This dynamic river's unique features, including the annual flood pulse [*Junk et al.*, 1989; *Sverdrup-Jensen*, 2002; *Lamberts*, 2006], create conditions conducive to the survival of some 20,000 plant species, 430 mammal, 1200 bird, 800 reptile and amphibian [*MRC*, 2010], and 850 fish species [*Hortle*, 2009], all of which (particularly the fish) provide income and food security for the basin's 60 million human inhabitants. Given the current absence of major military conflict, as well as concerns regarding climate change and food security, and an increased regional need for and interest in energy production and the income derived from it, the river and its tributaries have become attractive to hydropower developers [*MRC*, 2010; *Hirsch*, 2010; *Grumbine et al.*, 2012]. By 2030, the construction of at least 63 dams are expected to be completed, including at least 7 on the Lancang River and 56 on LMB tributaries [*MRC*, 2011]. Plans exist for 134 dams in total to be built in the LMB. These dams and their reservoirs could severely alter the natural flow of water and sediments through the river basin, as well as the ecosystem and local economies that depend on these regimes. However, given that the basin is still largely undeveloped, there still exist ample opportunities to build and operate dams in ways that reduce adverse impacts where possible. This dissertation explores such opportunities.

2 Organization of Dissertation

The five chapters (and appendices) presented in this dissertation describe the development of a methodology to (1) identify reservoirs that could significantly alter the Mekong basin's natural sediment regime, (2) assess alternative dam siting, design and operating policies that could improve sediment passage compared to current plans, and (3) quantify the losses in hydropower production that may be necessary to achieve improved sediment passage. To permit such evaluations, a sediment simulation model, *SedSim*, was developed in partnership with various water resources and energy ministries in Cambodia, Lao PDR and Vietnam. Details about the model are provided in the methodology sections of Chapter 2 and Chapter 3, as well as the *SedSim* documentation and user manual in the Appendix. Motivation for developing the *SedSim* model, rather than making use of existing modeling tools, is discussed in Section 3 of this Chapter.

Chapter 2 outlines a methodology useful for identifying reservoirs that could severely impact the local natural sediment balance. The chapter focuses on evaluating the potential for reservoir sedimentation in the Se San, Sre Pok and Se Kong tributaries of the Mekong River. These tributaries drain a set of adjacent watersheds that are important with respect to biodiversity and ecological productivity, and serve as a significant source of flow and sediment to the mainstream Mekong River. In addition to identifying impactful reservoirs in these sub-basins, this study seeks to (1) evaluate whether long-term reservoir storage capacity and energy production could be affected by sedimentation, and (2) discuss the motivation for, and potential barriers to, reservoir sediment management in the Mekong basin. Others have performed preliminary assessments of the potential for Mekong basin-wide sediment trapping [e.g., *Kummu et al.*, 2010; *Kondolf et al.*, 2013]. The work introduced in Chapter 2 benefits from these other studies and builds on them. Using daily rather than annual time step simulations, the methodology introduced here provides a more detailed assessment of reservoir operations, hydropower production, and inter- and intra-annual variations in trapping efficiency [*Lewis et al.*, 2013] that cannot be simulated using an annual time step. Additionally, this study addresses the interrelatedness of flow and sediment regime alteration and energy production.

Chapter 3 and Chapter 4 build on the findings from Chapter 2 by assessing alternative dam siting, design and operating policies that could improve sediment passage at planned dams that could be identified as impactful using the approach outlined in Chapter 2. In particular, Chapters 3 and 4 use *SedSim* to evaluate various sediment management options such as flushing and sediment routing at Lower Se San 2 Dam, which is proposed to be sited at the confluence of the Se San and Sre Pok Rivers. Chapter 4 also evaluates possible sediment management options (including sediment flushing and sediment bypassing) for Sambor Dam in Cambodia, which is proposed to be sited on the main stem of the Mekong River. Sambor Dam would control the flow of water and sediment from the Mekong River into Cambodia's Tonle Sap Lake, the most productive inland freshwater fishery in the world, and the Vietnam Delta, which produces large quantities of rice and fish. In addition to evaluating the effectiveness of various sediment management practices, Chapter 3 and Chapter 4 evaluate the losses in hydropower production that may be required to achieve improvements to the rivers' sediment regimes.

3 Motivation for Development of the *SedSim* Model

Since 1990, the Mekong basin has been flooded with models, especially hydrologic models. For example, there are now at least seven hydrodynamic models used to study the Mekong Delta and floodplains alone. Thus, researchers are beginning to argue that research effort is probably best devoted to application of existing models, rather than to the development of new models [*Johnston and Kummu*, 2012]. While this may be true of hydrologic models, the same cannot be said of sediment models. While a few of the many models developed for, or applied in, the Mekong basin do have sediment capabilities, including the Mekong River Commission (MRC) Decision Support Framework (DSF) [*MRC*, 2005] suite of models that includes SWAT, IQQM and ISiS, and the Variable Infiltration Capacity (VIC) model [*Costa-Cabral et al.*, 2007], sediment applications have been rare. There has not been a proliferation of sediment studies in the basin thus far primarily because modeling sediment production and transport, as well as trapping in reservoirs, is complex, and application of most sediment models requires sediment data that either do not exist, are in the process of being collected, are not of adequate quality, or are not adequately detailed (e.g., lack information about grain size distribution) [*ICEM*, 2010]. *SedSim*, however, was developed such that it is fully functional without detailed data sets, and should therefore be useful as a planning tool.

SedSim was developed specifically for use in the Mekong River Basin, but because it is generic and data driven it can be applied anywhere. The model performs a daily time-step mass-balance simulation of flow and sediment that is intended to predict in relative terms the spatial and temporal accumulation and depletion of sediment in river reaches (channels) and in reservoirs under different reservoir operating and sediment management policies. The model is distinguished from other available models because it has the ability to simulate within one simple tool the impact of sediment management strategies on the mass balances of sediment and water, as well as hydropower production, in large systems of rivers and reservoirs, within the limitations of existing data. The text that follows in this section elaborates upon these advantages.

The first major benefit of *SedSim* is that it can simulate both water and sediment (as well as hydropower) in reservoirs and channels within one model, rather than packaging together several models that each perform different tasks (e.g., reservoir operations, channel flow routing, sediment routing, etc.). *SedSim* was developed with the purpose of providing a simple screening tool to the technical staff members of various ministries in Vietnam, Cambodia and Lao PDR. Thus, it was desirable to avoid combinations of models that require more training and expertise. In some cases, separating simulation capabilities among several models creates errors because the models are unable to communicate about aspects of the simulation that are clearly interrelated. For example, using one model to simulate reservoir operations (including reservoir storage and releases) and another to track sediment accumulation and releases is problematic, because reservoir water storages and releases are necessarily dependent on the extent of sediment accumulation in the reservoir. This is the very reason that this work does not directly make use of the reservoir operations models others have built for use in certain areas of the Mekong Basin, such as the application of the HEC ResSim model in the 3S basins [*Piman et al.*, 2013].

Second, *SedSim* is offered on a platform (Microsoft Excel) that is likely to encourage its use by individuals from a variety of backgrounds, as (1) the software is free as long as Excel is available, and (2) Excel is a tool with which many people are familiar. Furthermore, the model is built in a computing language (Excel Visual Basic for Applications (VBA)) that ensures the model's features, assumptions and user interface can be easily modified by users knowledgeable in Excel VBA. Given we have included the technical staffs of water resources ministries in the process of developing the model, and continue to provide these ministries with training, it is more likely that these experts will propose or attempt beneficial improvements to the structure of *SedSim* than with closed-source models currently being used in the basin.

Third, *SedSim* has a distinct advantage over other models in that it was developed specifically to be used in circumstances in which data are sparse. The model was developed specifically to handle cases in which the data available are (1) annual sediment loads, and (2) lack information about grain size distribution. Conversely, if sediment rating curves already exist (or can be derived based on daily sampling measurements), as they do for parts of the main stem of the Mekong River, the user can just specify those parameters without conducting a calibration. The model can adapt to future data availability, as it is possible to simply specify daily sediment load production from other models (or from gage data) as time series of *SedSim* input data, should those data become available in the future.

Fourth, *SedSim* is designed for a pre-feasibility, screening level of water resources systems assessment. In other words, *SedSim* can consider reservoir sediment management practices such as flushing at multiple sites, while also simulating the impact of these practices on other downstream reservoir and stream channel sites at which such methods are not being implemented. Especially with regard to simulating sediment management practices, other available models permit very detailed assessments of sediment transport, which makes systems analysis of tradeoffs in large systems of reservoirs very difficult to explore. Detailed models require detailed data, and are not useful for planning-level simulations of large systems, particularly when sensitivity analysis is required. Detailed analysis is useful at the level of design of sediment management facilities and reservoir operational strategies. Conversely, *SedSim* is designed for a pre-feasibility, screening level of planning and evaluation of a variety of sediment management options. This is a particularly appropriate level of detail for modeling sediment management in the Mekong basin, because (1) roughly identifying the tradeoffs among hydropower, sediment and flow regimes is an important step before more detailed modeling is conducted, and can be generated at the same rapid pace at which dams are being planned; (2) the data required to conduct detailed modeling are not available for many proposed dam sites.

Fifth, *SedSim* offers users the option of simulating multiple sediment management techniques (e.g., flushing, sluicing, density current venting, bypassing and dredging). Simulating a variety of sediment management approaches typically requires the ability to alter a reservoir's operating policy. To do this with existing modeling tools being used in the Mekong basin, such as the MRC DSF suite, or other models, would require significant changes to the structure of these model suites.

It is important to briefly review some examples of the detailed tools that are available to model sediment flows through channels and reservoirs, aside from the MRC DSF suite of tools. A variety of detailed sediment transport models are available, most of which are one-dimensional

(1D), just as *SedSim* is. Such models typically only consider one dimension because the elongated geometry of reservoirs are conducive to consideration of only one dimension, and because models that consider more than one dimension require more extensive data and can ultimately be less robust. Within the 1D category, the more detailed, data intensive models are typically movable boundary models, examples of which include HEC RAS (formerly HEC-6), developed by the U.S. Army Corps of Engineers in 1991; GSTARS, developed by the U.S. Bureau of Reclamation [*Molinas and Yang*, 1986]; and FLUVIAL. More detailed, multi-dimensional models that have been applied to reservoir studies include TABS-2 [*Thomas and McAnally*, 1985] and SSIM [*Olsen et al.*, 1994]. There are two primary differences between such models and *SedSim*, both of which relate to the level of detail at which sediment is simulated. First, detailed 1-D models (e.g., HEC-RAS) assume an interrelationship between channel hydraulics and sediment transport, so there is feedback between the water and sediment components during channel transport. In contrast, *SedSim* ignores such feedbacks. For example, during each time step, these models first solve hydraulic transport equations, using the resulting hydraulic parameters to solve sediment transport equations. These transport equations are solved with the goal of determining the sediment transport capacity of each reach, which determines the scour or deposition of sediment from the bed when compared to the inflowing sediment load. As the bedded sediment changes, so does the channel geometry, which in turn impacts water hydraulics in the next time step. Second, more detailed models have the capability to conduct the approach outlined above for multiple sediment size classes.

Aside from the increased data requirements and inability to simulate sediment in large systems of reservoirs and channels, these more detailed models each have unique combinations of drawbacks that would render them ineffective given the goals of this studies described in

Chapters 2, 3 and 4. For example, detailed sediment transport models would need to be linked to external reservoir operations models, which is not a trivial task. Furthermore, despite the increased data requirements, some models (including GSTARS and FLUVIAL) do not even have the capability to simulate transport of clay and silt, which are two of the dominant sediment classes in reservoir transport and are critical for nutrient transport. Finally, such detailed models do not generally offer the capability to easily simulate sediment management techniques such as flushing. Often, flushing models are developed for individual reservoir studies, and may involve routing of as many as 10 sediment class sizes through the reservoir(s) of interest. Simulations may include two-dimensional representation of the flushing channel, and may benefit from development of a coupled physical model [*White*, 2001]. Less detailed flushing models do exist. One example of a sediment model that can simulate reservoir flushing and reservoir operations at the same level of detail as *SedSim* is described by *Chang et al.* [2003]. Once again, though, these models may have several limitations, including (1) inability to simulate additional sediment management techniques such as dredging, sluicing and bypassing; (2) inability to easily extend the model to analysis of networks of many reaches and reservoirs; (3) requirement that reservoir operations and sediment routing be conducted with separate models; and (4) lack of a user-friendly interface.

4 References

Baran E., and E. Guerin (2012), *Fish bioecology in relation to sediments in the Mekong and in tropical rivers*, Report for the Project "A Climate Resilient Mekong: Maintaining the Flows that Nourish Life" led by the Nat. Heritage Inst., WorldFish Cent., Phnom Penh, Cambodia, 52.

Chang, F-J., J.-S. Lai, and L.-S. Kao (2003), Optimization of operation rule curves and flushing schedule in a reservoir, *Hydrol. Process.*, 17, 1623-1640.

Costa-Cabral, M.C., J.E. Richey, G. Goteti, D.P. Lettenmaier, C. Feldkotter, and A. Snidvongs (2008), Landscape structure and use, climate, and water movement in the Mekong River Basin, *Hydrol. Process.*, 22, 1731-1746.

Grant, G.E. (2012), The Geomorphic Response of Gravel-bed Rivers to Dams: Perspectives and Prospects, in *Gravel-bed Rivers: Processes, Tools, Environments,* edited by M. Church, et al., Wiley.

Grumbine, E.R., J. Dore, and J. Xu (2012), Mekong hydropower: drivers of change and governance challenges, *Front. Ecol. Environ*., 10(2), 91-98, doi: 10.1890/110146.

Hirsch, P. (2010), The changing political dynamics of dam building on the Mekong, *Water Alternatives*, 3(2), 312-323.

Hortle, K.G. (2009), Fishes of the Mekong - how many species are there? *Catch and Culture,* 15, 4-12.

ICEM (2010), Hydrology and Sediment Baseline Assessment Working Paper, in *Baseline assessment report, Strategic Environmental Assessment of hydropower on the Mekong mainstream for the MRC*, pp. 85, Int. Cent. Environ. Manage., Hanoi, Vietnam.

Junk, W. J., P.B. Bayley, and R.E. Sparks (1989), The flood pulse concept in river-floodplain systems, in *Proceedings of the International Large River Symposium (LARS), Can. Spec. Publ. Fish. Aquat. Sci.*, edited by D. P. Dodge, pp. 110–127.

Kondolf G.M., Z. Rubin, C. Alford, J.T. Minear (2013), Cumulative sediment reduction to the lower Mekong River from planned dams, In Fukuoka S, Nakagawa H, Sumi T, Zhang H (eds), *Advances in River Sediment Research*, London, UK, Taylor and Francis.

Kummu, M., X.X. Lu, J.J. Wang, and O. Varis (2010), Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong, *Geomorphology*, 119, 181–197.

Lamberts, D. (2006), The Tonle Sap Lake as a productive ecosystem, *Int. J. Water Resour. Dev.*, 22(3), 481-495.

Lewis, S. E., Z. T. Bainbridge, P. M. Kuhnert, B. S. Sherman, B. Henderson, C. Dougall, M. Cooper, and J. E. Brodie (2013), Calculating sediment trapping efficiencies for reservoirs in tropical settings: A case study from the Burdekin Falls Dam, NE Australia, *Water Resour. Res.*, 49, 1017-1029, doi:10.1002/wrcr.20117.

Mahmood, K. (1987), Reservoir Sedimentation: Impact, Extent, Mitigation, *World Bank Tech. Rep. 71*, Washington, D.C.

Mekong River Commission (MRC) (2005), *Overview of the Hydrology of the Mekong Basin*, Mekong River Comm., Vientiane, November 2005, 73.

Mekong River Commission (MRC) (2010), *State of the Basin Report*, Mekong River Comm., Vientiane, 2010.

Mekong River Commission (MRC) (2011), *Basin Development Plan Programme Phase 2: Assessment of Basin-wide Development Scenarios*, Main Rep., Mekong River Comm., Vientiane, April 2011.

Molinas, A. and C.T. Yang (1986), *Computer Program User's Manual for GSTARS (Generalized Stream Tube model for Alluvial River Simulation)*, U.S. Bureau of Reclamation, Denver, CO.

Olsen, N. R. B., O. Jimenez, A. Lovoll, and L. Abrahamsen, (1994), Calculation of Water and Sediment Flow in Hydropower Reservoirs, *JAHR International Conference on Modeling, Testing and Monitoring of Hydropower Plants*, Budapest.

Power, M.E., W.E. Dietrich, and J.C. Finlay (1996), Dams and Downstream Aquatic Biodiversity: Potential Food Web Consequences of Hydrologic and Geomorphic Change, *Environ. Manage.,* 20(6), 887-895.

Sverdrup-Jensen, S. (2002), Fisheries in the Lower Mekong Basin: Status and Perspectives, *MRC Tech. Pap. 6*, Mekong River Comm., Phnom Penh, 103.

Thomas, W. A. and W.H.J. McAnally (1985), *User's Manual for the Generalized Computer Program System Open-channel Flow and Sedimentation TABS-2*, U.S. Army Waterways Experiment Station, Vicksburg, Miss.

Vörösmarty, C.J., M. Meybeck, B. Fekete, K. Sharma, P. Green, and J.P.M. Syvitski (2003), Anthropogenic sediment retention: major global impact from registered river impoundments, *Global Planet. Change*, 39(1–2), 169–190.

White, W. R. (2001), *Evacuation of Sediments from Reservoirs*, Thomas Telford, London.

CHAPTER 2

MANAGING FLOW, SEDIMENT, AND HYDROPOWER REGIMES IN THE SRE POK, SE SAN AND SE KONG RIVERS OF THE MEKONG BASIN[1]

Abstract

The Lancang/Mekong River Basin is presently undergoing a period of rapid hydropower development. In its natural undeveloped state, the river transports about 160 million metric tons of sediment per year, maintaining the geomorphologic features of the basin, sustaining habitats, and transporting the nutrients that support ecosystem productivity. Despite the importance of sediment in the river, currently little attention is being paid to reservoir sediment trapping. This study is devoted to assessing the potential for managing sediment and its impact on energy production in the Se San, Sre Pok and Se Kong tributaries of the Mekong River. These tributaries drain a set of adjacent watersheds that are important with respect to biodiversity and ecological productivity, and serve as a significant source of flow and sediment to the mainstream Mekong River. A daily sediment transport model is used to assess tradeoffs among energy production and sediment and flow regime alteration in multiple reservoir systems. This study finds that eventually about 40%-80% of the annual suspended sediment load may be trapped in reservoirs. Clearly, these reservoirs will affect the rivers' sediment regimes. However, even after 100 years of simulated sedimentation, reservoir storage capacities and hydropower production at most reservoir sites are not significantly reduced. This suggests that the strongest motivation for implementing measures to reduce trapped sediment is their impact not on hydropower production

[1] This chapter is reproduced with permission from John Wiley and Sons: Wild, T.B., and Loucks, D.P. (2014), *Water Resour. Res.,* 50, 5141-5157, DOI: 10.1002/2014WR015457, with modifications to conform to the required dissertation format.

but on fish migration and survival and on sediment dependent ecosystems such as the Vietnam Delta and Cambodia's Tonle Sap Lake.

1 Introduction

The Mekong basin is one of the world's most productive and diverse ecosystems. A shifting geopolitical landscape, including multiple wars, have kept the Lower Mekong River Basin (LMB) natural [*Hirsch*, 2010]. As such it has supplied the fish and other aquatic species that support the livelihoods of, and provide the primary source of protein for, more than 60 million people living in the basin [*Mekong River Commission (MRC)*, 2010]. The production of fish results from the natural hydrologic, sediment, and nutrient regimes in the river as its water flows 4,880 km from the Tibetan Plateau through the upper Mekong (or *Lancang*) River basin of China, and then through the Lower Mekong Basin (LMB), draining parts of Myanmar, Thailand, Lao PDR, Cambodia, and Vietnam. Given the current absence of major military conflict, as well as concerns regarding climate change and food security, and an increased regional need for and interest in energy production, the river and its tributaries have become attractive to hydropower developers [*MRC*, 2010; *Hirsch*, 2010; *Grumbine et al.*, 2012]. By 2030, the construction of at least 63 dams are expected to be completed, including at least 7 on the Lancang River and 56 on LMB tributaries [*MRC*, 2011b]. Plans exist for 134 dams in total to be built in the LMB. Dam construction is occurring at a particularly rapid pace on the Se San, Sre Pok and Se Kong (3S) tributaries (collectively called the '3S' basins, as shown in Figure 2.1).

Draining almost equal parts of Cambodia, Lao PDR and Vietnam, the 3S basins have a combined contributing watershed area of approximately 78,650 km^2 (about 10% of the Mekong River's 795,000 km^2 watershed). Currently 18 dams exist in the 3S basins, with 23 additional

Figure 2.1: Se San, Sre Pok, and Se Kong (3S) tributary basins to the Mekong River, showing existing and proposed hydropower dams. Based on data from *MRC* [2012].

Table 2.1: Summary of data related to existing and proposed 3S basins dams, and simulated sediment inflows and sedimentation.

Dam Name	Sub-basin[a]	Country ID[b]	Storage Capacity (10^6 m^3)	Installed Capacity (MW)	Scenario DF	Scenario FD	Mean Sed. Inflow ($Mt\ y^{-1}$) Unreg-ulated[c]	Mean Sed. Inflow ($Mt\ y^{-1}$) Reg-ulated[c]	Mean Trapped Sed. Load ($Mt\ y^{-1}$)
Lower Se San + Sre Pok 2 (LSS2)	SS, SP	C	1793	400	x	x	14.18	2.31-10.05	1.5-6.5
Lower Se San 3	SS	C	4598	243		x	4.43	1.63-1.91	1.54-1.56
Prek Liang 1	SS	C	72	35		x	0.26	0.12-0.16	0.06-0.08
Prek Liang 2	SS	C	102	25		x	0.17	0.17	0.09-0.14
Lower Sre Pok 3	SP	C	5599	204		x	7.60	3.56-3.73	3.16-3.44
Lower Sre Pok 4	SP	C	9000	143		x	4.00	1.6-2.33	1.58-2.14
O Chum 2	SS	C	0	1	Dam not modelled (too small)				
Houayho	SK	L	674	150	x	x	0.06	0.06	0.05-0.06
Xekaman 3	SK	L	142	250	x	x	0.20	0.2	0.11-0.16
Xekaman 1	SK	L	4804	322	x	x	1.00	0.54-0.89	0.54-0.83
Xekaman-Sanxay	SK	L	12	32	x	x	1.05	0.05-0.11	0-0.01
Xepian	SK	L	46	0	x	x	0.06	0.06	0.02-0.04
Xepian-Xenamnoy	SK	L	1092	390	x	x	0.15	0.17-0.19	0.17-0.18
Xe Katam	SK	L	127	61	x	x	0.08	0.08	0.06-0.07
Xekong 4	SK	L	10500	300		x	1.51	0.77-0.83	0.77-0.78
Nam Kong 1	SK	L	683	150	x	x	0.36	0.12-0.22	0.12-0.16
Xe Kong 3up	SK	L	187	105		x	1.65	0.14-0.19	0.07-0.09
Xe Kong 3d	SK	L	88	100		x	2.75	0.84-0.92	0.11-0.3
Xe Kong 5	SK	L	3300	330		x	0.73	0.74	0.67-0.73
Xe Kaman 2A	SK	L	21	64		x	0.55	0.11-0.2	0-0.01
Xe Kaman 2B	SK	L	333	100		x	0.49	0.23-0.32	0.18-0.19
Xe Kaman 4A	SK	L	19	96		x	0.07	0.07	0.03-0.05
Xe Kaman 4B	SK	L	34	74		x	0.05	0.05	0.03-0.04
Dak E Mule	SK	L	243	130		x	0.04	0.04	0.02-0.03
Xe Nam Noy 5	SK	L	10	20	x	x	0.02	0.02	0.01-0.01
Houay Lamphan	SK	L	481	88	x	x	0.04	0.04	0.04-0.04
Nam Kong 2	SK	L	166	74	x	x	0.25	0.07-0.25	0.06-0.2
Xe Xou	SK	L	2671	63.4		x	0.36	0.35	0.33-0.35
Nam Kong 3	SK	L	311	25		x	0.19	0.19	0.14-0.17
Upper Kontum	SS	V	174	250	x	x	0.10	0.1	0.08-0.09
Plei Krong	SS	V	1049	100	x	x	0.90	0.9	0.72-0.85
Yali	SS	V	1039	720	x	x	2.09	1.14-1.27	0.85-1.01
Se San 3	SS	V	87	260	x	x	2.18	0.22-0.51	0.08-0.11
Se San 3A	SS	V	81	96	x	x	2.26	0.2-0.51	0.08-0.1
Se San 4	SS	V	893	360	x	x	2.61	0.46-0.78	0.41-0.5

Se San 4A	SS	V	8	63	x	x	2.63	0.07-0.29	0-0.01
Duc Xuyen	SP	V	1088	49	x	x	0.32	0.32	0.3-0.32
Buon Tua Srah	SP	V	787	86	x	x	0.85	0.53-0.55	0.45-0.51
Buon Kuop	SP	V	37	280	x	x	2.31	1.49-1.56	0.06-0.28
Dray Hlinh 1&2	SP	V	3	28	x	x	2.58	1.47-1.76	0
Sre Pok 3	SP	V	243	220	x	x	2.73	1.59-1.91	0.65-1.01
Sre Pok 4	SP	V	114	70	x	x	2.77	0.65-1.31	0.2-0.28

[a] Tributary sub-basin: SS = Se San, SP = Sre Pok, SK = Se Kong.
[b] Country ID: C = Cambodia, L = Lao PDR, V = Vietnam.
[c] Mean annual sediment inflow (Mt y^{-1}) for each reservoir is shown for the unregulated system (no dams) and regulated system, and sediment trapping is shown for the regulated system. A range is provided for regulated inflows and trapping, representing simulated results from different assumptions regarding basin development and sediment size. Only one regulated inflow value is provided (rather than a range) at sites with no upstream reservoirs.

dams planned to be constructed, as summarized in Table 2.1 [*MRC*, 2012]. The 41 dams will provide 6,600 MW of installed hydropower capacity and over 50 billion m^3 of total storage capacity. Dams constructed in the 3S basins may threaten ecosystem health and productivity if they substantially alter the natural hydrologic and sediment regimes that sustain these ecosystems, and are expected to interfere with fish passage [*MRC*, 2010]. The Mekong basin is home to approximately 20,000 plant species, 430 mammal, 1200 bird, 800 reptile and amphibian [*MRC*, 2010], and 850 fish species [*Hortle*, 2009]. The 3S Rivers provide critical fish spawning and breeding grounds for about 40% of this biodiversity (329 fish species), including 17 fish species found nowhere else in the world [*Baran et al.*, 2013].

The 3S Rivers contribute a combined mean annual discharge of about 2,890 m^3/s, or about 20% of the Mekong River's 15,000 m^3/s mean annual discharge [*MRC*, 2005; *Adamson*, 2009]. Monsoon-driven discharge (June-November) accounts for about 80% of the annual runoff [*MRC*, 2005]. The basin’s exceptional productivity and biodiversity are driven by the annual flood pulse, which controls the river’s exchange of nutrient and sediment loads with its floodplains [*Junk et al.*, 1989; *Sverdrup-Jensen*, 2002; *Lamberts*, 2006]. Researchers are just beginning to explore the potential impact of hydropower production on the 3S rivers' flow regimes [*Ty et al.*, 2011, 2012; *Piman et al.*, 2013, 2014]. However, there remains a gap in knowledge about the impact of these hydropower dams on the sediment balance, both on the 3S Rivers and the Mekong River. The few studies addressing this issue have demonstrated that there exists significant potential for sediment trapping in the 3S basins [*Kummu et al.*, 2010; *Kondolf et al*., 2013; *Wild and Loucks*, 2012a].

The Mekong River produces approximately 160 million metric tons of suspended sediment per year (Mt y^{-1}) [*Milliman and Meade*, 1983], while sediment production in the 3S basins is thought to be 10-25 Mt y^{-1} (or roughly 6%-16% of the Mekong basin's sediment load) based on limited data [*Sarkkula et al.*, 2010; *ICEM*, 2010]. Approximately half of the Mekong basin's load is generated in the Upper Mekong Basin in China [*Gupta and Liew*, 2007; *Walling*, 2008], while the remaining half is produced in the LMB [*Clift et al.*, 2004]. Dams in China may trap most of the 80 Mt y^{-1} generated in China [*Lu and Siew*, 2006; *Fu and He*, 2007; *Kummu and Varis*, 2007; *Kondolf et al., 2013*], and combined with dams in the LMB, the river's total sediment discharge could be reduced by 51%-96%, depending on a variety of assumptions, including the number of dams ultimately constructed [*Kummu et al.*, 2010; *ICEM*, 2010; *Kondolf et al., 2013*]. Any sediment discharged from the 3S basins could ultimately represent a significant portion of the sediment load reaching critical Mekong ecosystems such as the Vietnam Delta and Cambodia's Tonle Sap Lake, which provide food and economic security for tens of millions of people.

This study focuses on sediment trapping in reservoirs. Sediment trapping can have three critical impacts over time: (1) alteration of the morphology of the river, which affects important physical features and habitats [*Grant*, 2012; *Power et al.*, 1996]; (2) reduction of nutrients (particularly phosphorus) and organic matter that are transported primarily by clay and silt [*Baran and Guerin*, 2012]; and (3) reduction of reservoir storage capacity and hence energy production and reliability, as well as other benefits dams provide [*Mahmood*, 1987; *White*, 2001]. Critical habitat areas that are sensitive to sediment starvation include the Vietnam Delta, which may subside without sediment replenishment [*MRC*, 2010]; deep pools, which provide refuge and spawning grounds for migratory fish [*Halls et al.*, 2013]; and Cambodia's floodplains and Tonle Sap Lake, both of which require an influx of sediment and nutrients to remain productive. Additionally, reservoirs induce a variety of effects on rivers downstream of dams, including releasing clear water that may scour sediment in downstream channels, and altering the river's flow regime and thus its ability to transport sediment [*Kondolf*, 1997; *Brandt*, 2000; *Grant et al.*, 2003; *Petts and Gurnell*, 2005; *Schmidt and Wilcock*, 2008]. Sediment can also clog intakes and outlet works, damage turbines, create dam safety issues and increase decommissioning costs [*Morris and Fan*, 1998]. For all of these reasons, sediment trapping should be of concern among key basin stakeholders, including dam operators, owners and investors; power consumers; and those with environmental interests.

This paper has three purposes. The first is to assess the extent to which sedimentation will occur in existing and planned 3S basins reservoirs if sediment is not managed. This will help identify those reservoirs that could benefit from sediment management, and motivate the importance of future studies to assess the potential effectiveness of specific sediment management techniques at those sites (to build upon the initial assessments of *Annandale* [2012a, 2012b, 2012c] and *Wild and Loucks* [2013, 2014a]). Second, this paper identifies some of the potential economic and political barriers that could reduce the likelihood that sediment management practices are ultimately implemented. Third, this paper introduces a methodology, including a simulation model, developed for use by various government ministries in the Mekong basin to assess tradeoffs among energy production, sediment regime alteration, and flow regime alteration in reservoir systems. We also assess the relative importance of various assumptions regarding the values of uncertain model parameters. The Mekong Basin is developing rapidly, so new data will inevitably become available and perhaps change some of the model results reported here. However, the methodology presented here may serve as a useful template for conducting additional LMB analyses in the future.

Others have performed preliminary assessments of the potential for Mekong basin-wide sediment trapping [e.g., *Kummu et al.*, 2010; *Kondolf et al.*, 2013]. The work introduced here benefits from these other studies and builds on them. Using daily rather than annual time step simulations, the methodology introduced here provides a more detailed assessment of reservoir operations, hydropower production, and inter- and intra-annual variations in trapping efficiency [*Lewis et al.*, 2013] that cannot be simulated using an annual time step. Additionally, this study addresses the interrelatedness of flow and sediment regime alteration and energy production.

2 Methodology

2.1 Model Background

Since 1990, the Mekong basin has been flooded with hydrologic and hydrodynamic models [*Johnston and Kummu*, 2012]. Conversely, development and application of sediment models have been rare not only because modeling sediment production, transport, and trapping is complex, but also due to a lack of sediment data [*Walling*, 2005, 2008; *Wang et al.*, 2011]. For this study we developed a daily simulation model, called *SedSim*, specifically for use in the Mekong River Basin. It can function using only an estimate of average annual sediment load [*Wild and Loucks*, 2012b]. We use the model to predict in very relative terms the spatial and temporal accumulation and depletion of sediment in river channels and in reservoirs under different operating and sediment management policies. *SedSim* simulates flow, sediment and hydropower production, given various multiple reservoir sediment management techniques (e.g., flushing, sluicing, density current venting, bypassing, and dredging). The model is one-dimensional and deterministic. Its basic elements are reservoirs, hydropower plants and river channels (reaches). *SedSim* provides LMB water and energy managers in government ministries with a Microsoft Excel-based screening tool that is easily used and modified as desired. The purpose of *SedSim* is to identify the more promising management alternatives that can then be evaluated in more detail with more sophisticated and data-intensive models.

2.2 Model Data

For this study average daily reservoir inflows are generated from a calibrated Soil and Water Assessment Tool (SWAT) model maintained by the *MRC* [*MRC*, 2011a]. Given SWAT generated inflows, *SedSim* is used to generate sediment concentrations (as described below) and simulate sediment trapping, as well as to conduct reservoir operations and channel routing. Reservoir and dam characteristics were obtained from *MRC* [2012].

Reliable and extensive sediment data sets for the 3S Rivers are not publicly available. Sparse sediment data are available from a few gage stations in Vietnam, but these data are of uncertain quality and are mostly confined to the upper-most sections of the Sre Pok and Se San

Rivers (*Power Engineering Consulting Joint Stock Company (PECC1)*, 2013). Recent sediment sampling efforts in the 3S basins may permit calibrating and validating a SWAT model to generate daily sediment loads, but until those data become available, the best available sediment load estimates are provided by *Kondolf et al.* [2011]. They partitioned the 80 Mt y^{-1} of sediment thought to be generated in the LMB among eight geomorphic regions, which were delineated based on climatic, geologic, topographic, and tectonic features. The 3S basins include two such regions (the Tertiary Volcanic Plateau and the Kon Tum Massif), which are estimated to produce specific sediment yields of about 280-290 tons km^{-2} yr^{-1}. The product of the specific sediment yield and the local (incremental) contributing watershed area (km^2) for a particular reservoir provides an estimate of the local mean annual sediment yield for a reservoir. This approach results in 22.7 Mt y^{-1} of sediment production in the 3S basins, which is within the 10-25 Mt y^{-1} range of values suggested by others [*Sarkkula et al.*, 2010; *ICEM*, 2010]. The focus of this study is on the suspended sediment load. Bed load is often as high as 10%-20% of the suspended load in many river basins [*Turowski*, 2010], although sediment sampling will be required to ascertain grain size distribution of 3S basins sediment. Absent sediment management operations, most of the 3S basins bedload is likely to be trapped in reservoirs.

Annual sediment loads are partitioned into daily sediment loads by employing a rating curve [*Milliman and Meade*, 1983; *Morehead et al.*, 2003] based on the power regression of suspended sediment concentration, C_s (kg/m^3), on discharge, Q (m^3/s), as given by Eq. (2.1)

$$C_s = aQ^b \tag{2.1}$$

Values for parameters “a” and “b” are determined for each incremental input location (e.g., reservoir site). At each location, *SedSim* calibrates the “a” value given a specified “b” value, with the goal of generating the predicted mean annual sediment load inflow for each reservoir site (based on specific sediment yield). The selection of each "b" value is discussed later. The calibration is performed under the assumption that the 3S basins are in relative balance when no reservoirs exist, exporting approximately what is eroded on an annual average basis [*Kondolf et al.*, 2011]. Indeed, studies have confirmed that the Mekong River's sediment load has remained relatively stable over the past 3,000 years [*Ta et al.*, 2002]. The approach given by Eq. (2.1) does not account for the possibility that watersheds may exhibit seasonal differences in sediment rating curve parameters. No significant seasonal differences were observed in evaluating the limited available sediment data for the 3S Rivers (*PECC1*, 2013).

The fraction of inflowing sediment mass trapped during each time period, or trapping efficiency, is determined using the *Brune* [1953] curve method, and is a function of sediment size and residence time of water in the reservoir. Residence time can change throughout the simulation. Declining storage capacity decreases trapping efficiency, which is an important but often neglected feedback process [*Minear and Kondolf*, 2009]. While there are other methods for estimating trapping efficiencies (e.g., *Churchill* [1948]), the Brune method has been shown to provide adequate long-term reservoir trapping efficiency estimates for ponded reservoirs throughout the world [*Morris and Fan*, 1998]. Many previously conducted Mekong Basin studies have already applied the Brune method, which makes the results of this study easier to compare to others [*Fu and He*, 2007; *Kummu and Varis*, 2007; *Kummu et al.*, 2010; *Kondolf et al.*, 2013]. Within the reservoir's storage capacity, the volume occupied by settled sediment mass depends on its bulk density, which is determined in part by the sediment composition, the extent to which the sediment is continuously submerged in water, and compaction processes, none of which are considered in this study. Instead, the bulk density of sediment is assumed to be 1200 kg/m^3, based on the reported density of sediment in the Vietnam Delta [*Xue et al.*, 2010]. Based on a study by *Lara and Pemberton* [1963] of over 100 reservoir sites, 1100-1500 kg/m^3 is a reasonable range for the density of reservoir sediment deposits.

2.3 Other Important Assumptions

Although only 21 years of flow data are available, simulations are conducted for 100 years by repeating the 21-year daily flow sequence. Simulations are conducted for a 100-year span, rather than 21 years, because this is often the assumed lifetime of a reservoir, and thus it was of value to report sediment accumulation over 100 years. This assumption has no effect on simulated flow or energy production statistics, but does make simulation of sedimentation more realistic. Simulating sedimentation for 100 years, rather than for 21 years and extrapolating results to 100 years, captures the effect of sediment accumulation reducing the reservoirs' trapping efficiencies over time. Note, however, that despite the 100-year simulation horizon, the hydrologic record is of limited length and therefore may not account for high-magnitude, low-frequency flood events that carry significant quantities of sediment.

Next, the possible impacts of climate change are not considered in this study for two reasons. First, results will demonstrate that different flow regimes caused by different operating policies do not result in significant changes to 3S basins sediment trapping. Thus, climate change-induced alterations to flows (and therefore to reservoir operating policies) are not likely to significantly affect the trapping efficiency of sediment in the 3S basins. Second, it is not possible to account for the effect of an altered natural flow regime on sediment production within the sediment production framework outlined above. Simulated climate change-induced daily flows from the SWAT model are available, but a SWAT model is not yet accurately calibrated for sediment production in the 3S basins. Thus, these new water flows would need to be used to generate daily sediment loads from target annual sediment yields (t km^{-2} yr^{-1}), but there is no justifiable way to develop new target annual sediment yields. Global and regional climate models generally predict increased wet season flows and reduced dry season flows for the 3S basins, depending on the climate model and climate change scenario assumed (*Piman et al.*, 2014; *Ty et al.*, 2012). Changes to patterns in the intensity, duration and frequency of rainfall events may increase soil erosion in the watershed. However, translating erosion into sediment yield is very difficult to reliably model without detailed data and an understanding of the dynamics of sediment buffering and storage in a watershed undergoing land use change [*Walling*, 2009; *Wisser et al.*, 2013]. Decisions about dam construction, including the existence of sediment management facilities, may be made at many sites before such issues can be accurately modeled.

2.4 Sensitivity Analysis

The quantity of sediment that is deposited in a reservoir depends on many assumptions. Most of the assumptions in *SedSim* are taken here to be known with certainty (e.g., reservoir storage capacities and outlet release capacities). A smaller subset of factors and assumptions impacting results are taken here to be less certain and are thus subject to sensitivity analyses, as described below.

2.4.1 Extent of basin dam development (i.e., number and location of reservoirs in the 3S basins)

Three scenarios are considered:

i) *Unregulated Scenario*. No dams.

ii) *Definite Future (DF) Scenario*. This scenario includes 25 dams (13 in Vietnam, 1 in Cambodia, and 11 in Lao PDR) that are either existing, under construction, or expected to be constructed in the near future (next five years, or by 2018), at a total installed capacity of 4.5 Gigawatts (GW).

iii) *Full Development (FD) Scenario*. This scenario includes all 41 existing, under construction and planned dams (13 in Vietnam, 6 in Cambodia, and 22 in Lao PDR), at a total installed capacity of 6.6 Gigawatts (GW).

2.4.2 Reservoir operating policies

Data regarding planned operating policies in this rapidly changing basin are difficult to acquire. Many reservoir operating policies are simply unknown at this time. Given the largely uncoordinated nature of basin development, operators are likely to be adapting their strategies in real time as the unknown policies of upstream reservoirs become available. So, three separate system policies (similar to those proposed by *Piman et al.* [2013]) are simulated to provide reasonable bounds on the range of possible future outcomes that could result from different combinations of operating policies throughout the basin.

i) *Full supply level policy (FSL)*. This is a run-of-river policy with the goal of maintaining the water surface elevation at the upper level (or full supply level) of the active storage zone.

ii) *Low supply level policy (LSL)*. This policy attempts to maintain the water surface elevation in the reservoir at the bottom of the reservoir's active storage zone (i.e., the low supply level). From a practical standpoint, this represents a flood control policy.

iii) *Seasonal variation (SV) policy*. This policy attempts to reduce spilling by filling the reservoir during the wet season and emptying the reservoir during the dry season.

2.4.3 Sediment grain size

Three curves proposed by *Brune* [1953] are simulated to reflect that different fractions of inflowing sediment are trapped depending on the size and type of sediment being deposited: the lower trapping curve for colloidal, dispersed and fine-grained particles; the upper trapping curve for flocculated and coarse sediments; and the median (standard) trapping curve.

2.4.4 Parameters “a” and “b” in Eq. (2.1), used to generate incremental sediment loads in the local sub-watersheds (between reservoir sites)

A value for “b” in Eq. (2.1) must be assumed so that an “a” value can be calibrated. Thus, the selection of “b” affects the value of “a”. For sensitivity analysis, “b” values are varied in the range from 0.2 to 1.6, and corresponding “a” values are calibrated. This is a reasonable range given the rating curve relationships established for the Mekong River [*Walling*, 2008; *Wang et al.*, 2011] and on the 3S tributaries using very limited gage data (*PECC1*, 2013).

3 Results and Discussion

3.1 Energy Production and Flow Regime Alteration

Figure 2.2 demonstrates average annual energy production for each of the three simulated reservoir operating policies (in both development scenarios) during the 100-year simulation, and what portions of that production come during the dry (December-May) and wet (June-November) seasons. Sedimentation is not significant enough to reduce total energy production during the 100-year simulation horizon. Dry season energy is highly valuable in the Mekong basin given the lower flows and increases in basin temperature that occur during this time. In general, reducing wet season production and increasing dry season production represents increased firm power, which can be more profitable than maximizing annual energy production. Firm power is especially critical in LMB countries, where the absence of interconnected, regional energy grids magnifies the importance of patterns in energy production at any given dam.

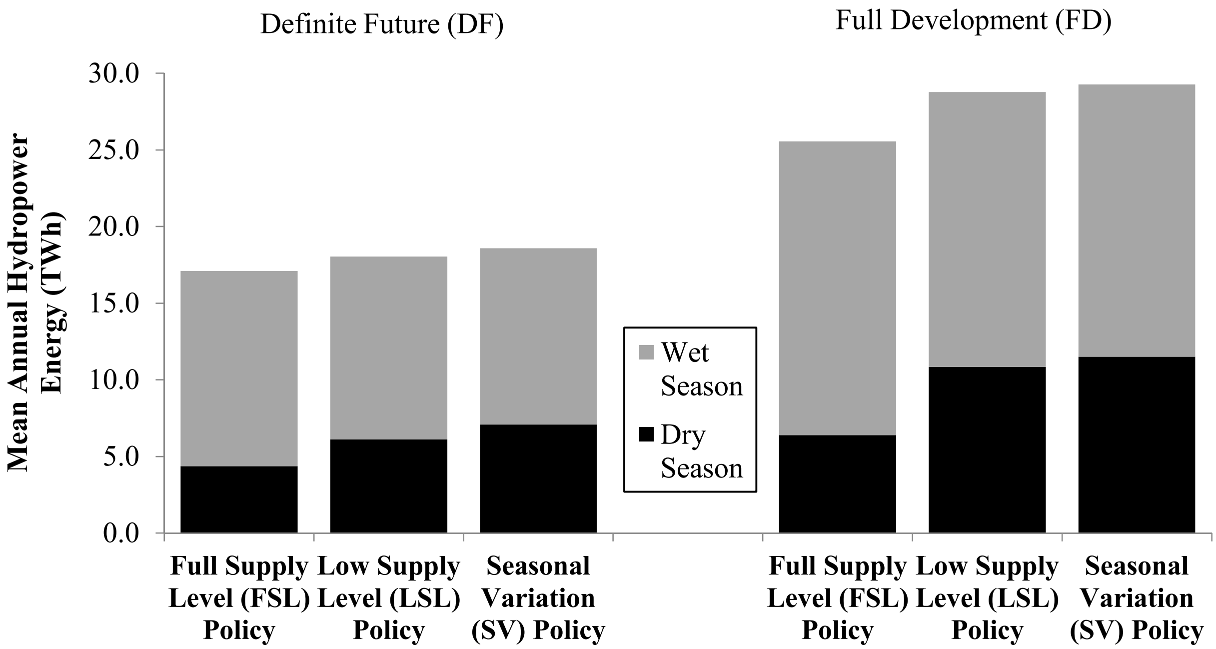


Figure 2.2: Simulated mean annual 3S basins hydropower energy production in Terawatt hours (TWh) for two development scenarios (Definite Future (DF) and Full Development (FD)) and three different system operating policies (Full Supply Level (FSL), Low Supply Level (LSL) and Seasonal Variation (SV)). Annual energy production is divided into dry season and wet season production.

In the DF scenario, the SV policy produces the highest mean annual energy of the three operating policies (18.6 TWh), although the LSL and FSL policies produce similar annual energy (18 TWh and 17.1 TWh, respectively). In the FD scenario, as expected, the addition of 16 dams significantly increases energy output. Once again, the SV policy produces the highest mean annual energy (29.4 TWh). In the DF scenario, the SV policy produces 7.1 TWh of dry season energy, which represents a 52% increase compared to the FSL policy and a 16% increase compared to the LSL policy. In the FD scenario, the 11.5 TWh of dry season energy represents increases of 80% and 6% compared to the FSL and LSL policies, respectively.

While the SV policy produces the highest mean annual energy, differences in energy production among policies are unexpectedly insignificant. This occurs for two reasons. First, the LSL and SV policies become very similar when simulated, effectively reducing the study to two policies (SV and FSL). Second, the mean annual energy produced by the FSL policy is reduced due to significant spilling. Both of these results occur because reservoir outlet release capacities are inadequate for maintaining the specified operating policy at numerous sites, particularly in the wet season.

Relatively few studies exist against which the energy estimates generated in this study can be compared. *Piman et al.* [2013] simulated three similar operating policies in the 3S basins, but differences in energy production among the operating policies differed from the results presented here due to differences in modeling assumptions. It is difficult to calibrate reservoir operations models for the 3S basins due to a lack of accurate and reliable information regarding existing and planned reservoir operations and power production.

Results show that the flow regime would benefit from run-of-river operations (FSL policy) compared to the SV policy. Figure 2.3 demonstrates that energy-focused policies tend to trim wet season peaks and elevate dry season low flows, whereas the FSL policy maintains the natural flow regime. These impacts are more prevalent if all 41 dams are built than if only the DF scenario's 25 dams are built. Only the FSL policy is capable of exactly reproducing important Mekong hydrologic features. For example, these features include flood peaks, which drive the basin's productivity; and spates, which are spikes in flow that offer spawning cues to migratory fish as the river transitions from the dry season to the wet season [*MRC*, 2009]. As important as the natural hydrologic regime is to the valuable Mekong ecosystem, 3S basins-wide FSL operations would reduce annual energy production (mainly due to increased wet season spilling) and significantly reduce firm power (dry season average energy production), without significantly reducing sediment trapping.

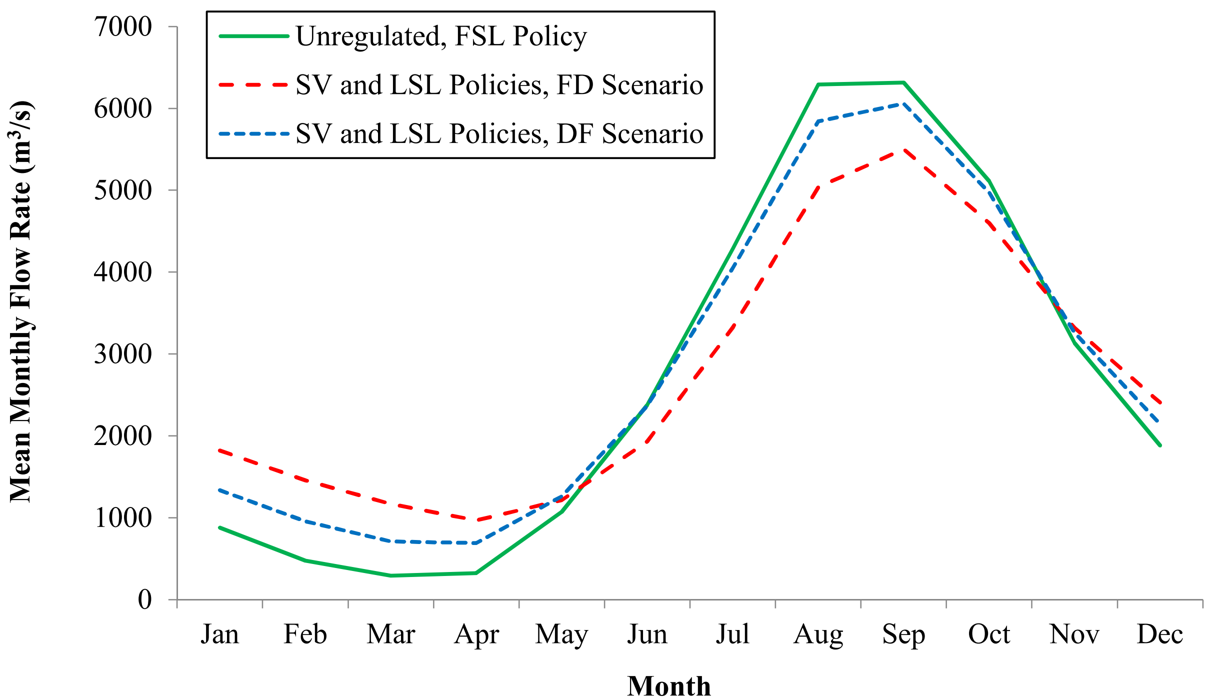


Figure 2.3: Simulated mean monthly flow rate (m^3/s) discharged from the outlet of the 3S River basins in the Definite Future (DF) and Full development (FD) scenarios for three different system-wide operating policies. The Full Supply Level (FSL) run-of-river policy was nearly identical to the 3S basins unregulated outflow, and only appears once because it was nearly identical in both development scenarios. The Low Supply Level (LSL) and Seasonal Variation (SV) operating policies resulted in similar basin outflows and are thus plotted together for each development scenario.

3.2 Reservoir Sedimentation

The three simulated operating policies outlined previously result in changes in basin-wide sediment trapping (the percentage of sediment produced in the 3S basins that is trapped in reservoirs) of 0%-2%. This change is insignificant given the uncertainty of sediment trapping estimation employed here. Changes in operating policy impact sediment trapping at 16 of the 41 reservoir sites. However, changing operating policies does not produce a consistent effect on trapping at those 16 sites, and the sites account for a relatively small percentage (less than 20%) of basin-wide sediment trapping. This result does not suggest that operating policies do not affect the 3S basins' sediment outlook. In reality, individual reservoirs may conduct operations that are highly detrimental to the local sediment balance (e.g., peaking), which can result in significant channel-based sediment scour and deposition over short periods of time and varying spatial scales.

There are a few explanations for the insignificant effect of changes in operating policy. First, each reservoir's trapping efficiency changes as a function of each reservoir's residence time. Among the three operating policies, total water storage does not vary significantly because the active storage zones, within which water levels fluctuate, are only fractions of the total storage volumes. Water storage volumes below the active storage zones are frequently very large and produce significant trapping. Outflows certainly vary among the three policies, but not enough to cause large changes in residence times. Second, at large reservoirs, where residence times are high and where much of the significant trapping in the basin occurs, differences in residence time (caused by differing operating policies) result in very small changes in trapping efficiency. Third, the LSL policy when simulated is similar to the SV policy, thereby effectively reducing the study to two operating policies.

Next, changes in the values of the incremental sediment load generation parameters "a" and "b" do not have a significant impact on basin-wide sediment trapping because of the manner in which sediment calibration is performed. Changing the "b" value and re-calibrating the "a" value is only affecting how the mean annual sediment load is distributed among the simulation's daily flow events. For example, increasing the "b" value (e.g., from 1.0 to 1.5) distributes more of the sediment load generation to the wet season, which is when the average reservoir trapping efficiency is lowest due to increased net outflows and reduced residence time. The difference in basin-wide trapping percentage induced by varying "b" values from 0.2-1.6 is insignificant (1%-2%), depending on the combination of other assumptions employed. As variation of the sediment rating curve parameters does not significantly affect trapping, a value of 1.0 is assumed for the remaining analysis. Numerous studies have confirmed that more of the basin's annual sediment load is generated in the early portion of the wet season, rather than throughout the wet season (e.g., *Walling* [2008]). While our approach to varying "b" values does not explicitly account for this condition, these results suggest that doing so would not significantly affect results reported here at the annual, basin-wide trapping scale.

Figure 2.4 summarizes the simulated mean annual percentage of 3S basins sediment load that is trapped in reservoirs, as a function of different levels of future dam development and sediment size. Discussion focuses on trapped percentages, rather than sediment mass trapped, to generalize the analysis given the current uncertainty regarding actual sediment loads generated in the 3S basins. Trapping efficiencies are relatively unaffected by the quantity of sediment assumed to be generated in the 3S basins. Accumulation of sediment over time does slowly reduce storage capacity and ultimately trapping efficiency, but the effect is insignificant. (For example, in the FD scenario, using the median sediment size, the mean basin-wide trapped percentage declines by about 2% as a result of running the simulation for an extended period of time, from about 77% in a 21-year simulation to about 75% in a 100-year simulation). Given that 22.7 Mt y^{-1} is already at the upper end of the generally accepted 3S basins production range (10-25 Mt y^{-1}), the impact of the magnitude of deposited sediment on trapping efficiency appears to be insignificant. For the same reason, trapping efficiencies reported here would not significantly decrease if trapped loads are increased by 10% to account for bedload trapping. Likewise, trapping efficiency estimates do not change much if sediment bulk density, which affects the volume of deposited sediment mass, is varied in the range of 1100-1500 kg/m^3.

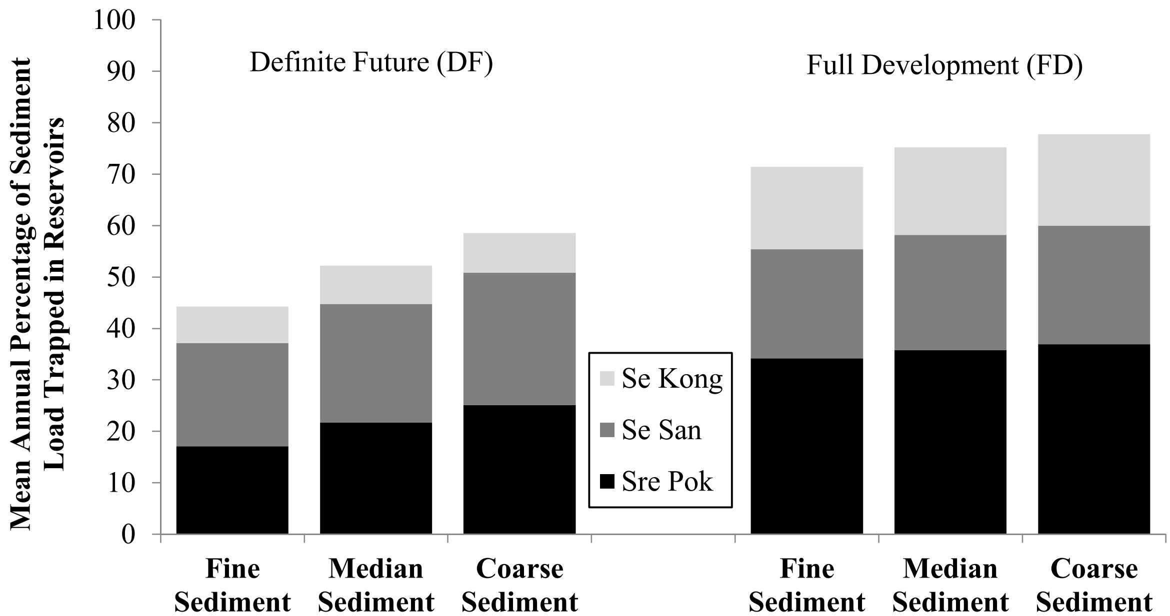


Figure 2.4: Simulated mean annual percentage of the 3S basins sediment load (22.7 Mt y^{-1}) that is trapped in reservoirs, assuming no sediment management is practiced. Results are displayed for a variety of assumptions, including trapping for fine, median, and coarse sediment and two levels of development (Definite future (DF) and Full Development (FD)).

In the DF scenario, 44% to 59% of 3S basins sediment load is trapped in reservoirs depending on sediment size, whereas in the FD scenario, trapping varies between 71% and 78%. In other words, 10-13.3 Mt y^{-1} of sediment (out of 22.7 Mt y^{-1}) is trapped on average in reservoirs in the DF scenario, and 16.2-17.7 Mt y^{-1} is trapped in the FD scenario. Whether 10 Mt y^{-1} or 17.7 Mt y^{-1} is trapped, the trapped quantity is 6%-11% of the 160 Mt y^{-1} transported by the Mekong River to critical Mekong ecosystems such as Tonle Sap Lake and the Vietnam Delta. Given that LMB reservoirs throughout the Mekong basin upstream of the 3S basins could trap 51%-96% of the approximately 137 Mt y^{-1} produced there [*Kummu et al.*, 2010; *ICEM*, 2010; *Kondolf et al., 2013*], the 10-17.7 Mt y^{-1} of trapping in the 3S basins could represent a significant percentage (13%-76%) of the Mekong basin's total sediment load. The 10-17.7 Mt y^{-1} of sediment trapped over 100 years represents about 0.8-1.5 billion m^3 of sediment prevented from replenishing critical Mekong ecosystems, particularly the Vietnam Delta, which could require sediment replenishment to survive predicted rising sea levels [*MRC*, 2010].

The effect of assumed sediment size is not as significant as the effect of the selected development scenario. The increase in the trapped percentage of the 3S basins sediment load from the DF scenario to the FD scenario is 27% for fine sediments and 19% for coarse sediments. Conversely, the difference in trapping between the two size classes is only 6% for the FD scenario and 14% for the DF scenario. Depending on sediment size assumptions, 4-6 additional Mt y^{-1} are trapped due to the addition of the 15 planned dams in the FD scenario, 58% of which comes from reservoirs on the Se Kong River. The remainder would be trapped in five proposed Cambodian reservoirs: Lower Se San 3, Prek Liang 1, Prek Liang 2, Lower Sre Pok 3, and Lower Sre Pok 4.

There are two primary reasons why varying sediment size does not produce as much uncertainty in trapping as does varying the extent of dam development. First, the Sre Pok and Se San Rivers are planned to be fully developed reservoir cascades. This creates a cascade trapping efficiency (93%, assuming median size sediments) that is much higher than the average individual trapping efficiency of the dams. The simulation results demonstrate that because almost every dam in the cascade has an opportunity to trap sediment generated upstream, the number of dams in the cascade becomes more important to sediment trapping than the dams' individual trapping efficiencies. Second, many of the reservoirs have lengthy residence times and high trapping efficiencies. While switching from the fine to median to coarse sediments produces significant variation in trapping efficiency at individual reservoirs having lower residence times, there is much less difference in sediment trapping rates for different sediment sizes at reservoirs having higher residence times. More than half of the reservoirs have less than a 10% spread in trapping efficiency among the sediment sizes due to high residence times.

Figure 2.5a and Table 2.1 show that a significant fraction of the 3S basins total trapping is expected to take place at four planned Cambodian dams: Lower Se San + Sre Pok 2 (400 MW, referred to henceforth as Lower Se San 2 (LSS2)), Lower Se San 3 (LSS3, 243 MW), Lower Sre Pok 3 (LSP3, 204 MW), and Lower Sre Pok 4 (LSP4, 143 MW). Sediment trapping error bars in Figure 2.5a show the sensitivity of these trapping estimates to sediment size and basin development assumptions, though for many reservoirs these errors bars are too small to be visible. If all four dams are constructed, they would trap 48% of the 3S basins sediment load expected to be trapped in reservoirs (8.5 Mt y^{-1} of 17.7 Mt y^{-1}), and would produce 21% of 3S basins annual energy and 22% of its dry season energy. Figure 2.5a also shows that the reservoirs with the largest storage capacities are generally trapping the most sediment. Note that the

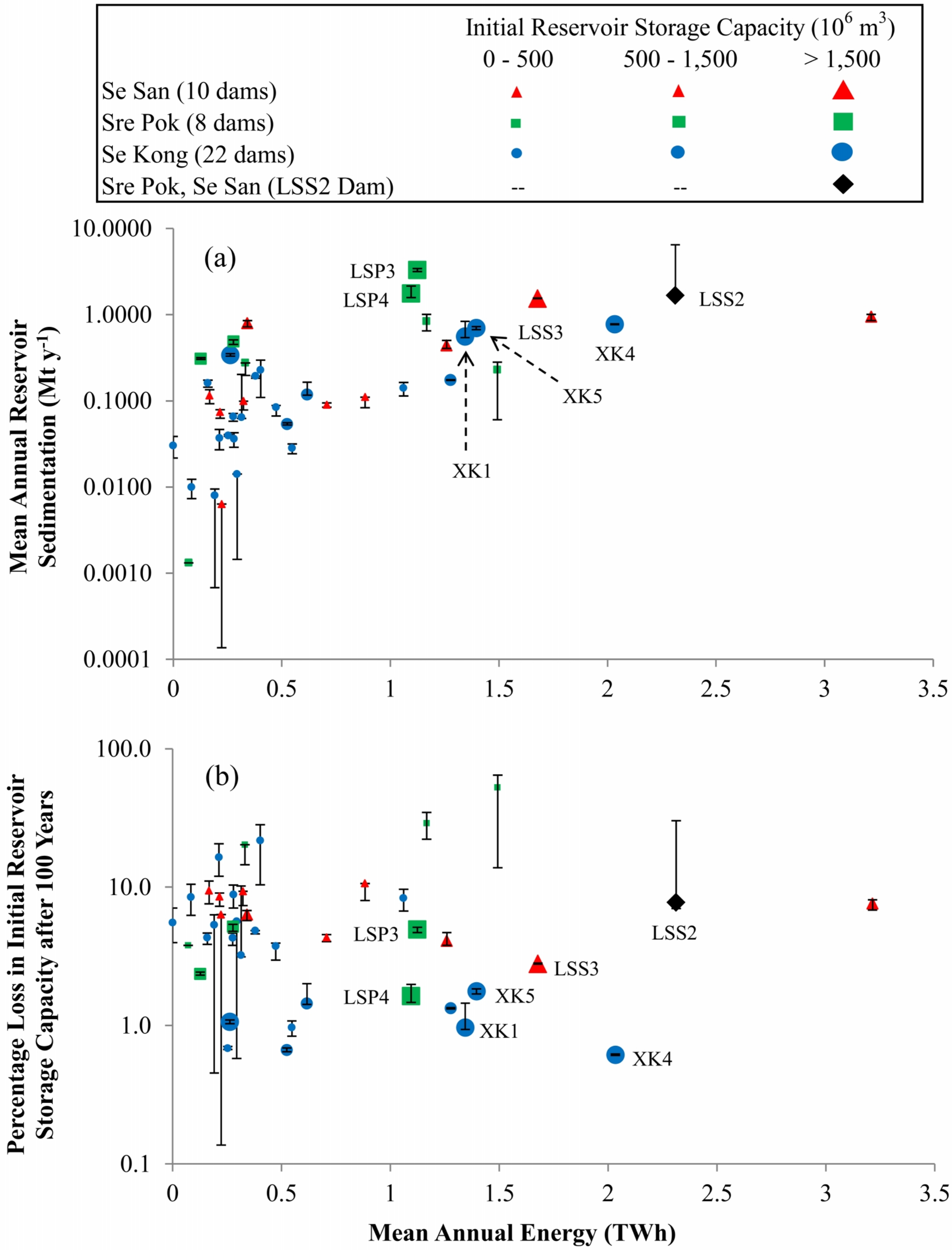


Figure 2.5: Simulated (a) mean annual sedimentation (or trapped sediment load) (Mt y^{-1}) and (b) loss in reservoir storage capacity after 100 years, in each 3S basins reservoir (grouped by tributary) vis-à-vis the mean annual energy produced at each reservoir (assuming the SV system operating policy). Ordinate axes are logarithmic. The plotted point that appears for each reservoir represents the FD scenario and median sediment size assumption, while the size of each point reflects the relative initial total storage capacity of each reservoir. The error bars that extend from each of these points represent results for all combinations

of assumptions regarding basin development (DF and FD scenarios) and sediment size. The four dams expected to trap the most sediment are labeled, including Lower Se San 2 (LSS2), Lower Se San 3 (LSS3), Lower Sre Pok 3 (LSP3) and Lower Sre Pok 4 (LSP4), as are dams expected to trap the most sediment on the Xe Kong tributary, including Xe Kong 5 (XK5), Xe Kong 4 (XK4), and Xekaman 1 (XK1).

ordinate axes in Figure 2.5 are in logarithmic scale to improve visibility of data points corresponding to reservoirs with lower trapping. Thus, it is important to note that while it may not be obvious from Figure 2.5a, there is a very large difference in sediment trapping between the few reservoirs trapping the most sediment and the other reservoirs.

The LSS2 Dam is expected to be constructed in the near future at the confluence of the Sre Pok and Se San Rivers. The construction dates of the remaining Cambodian dams appear to be less certain. Even if LSS2 is the only Cambodian dam constructed in the 3S basins (i.e., the DF scenario), 24% of 3S basins sediment load (5.44 Mt y^{-1} of 22.7 Mt y^{-1}) is still trapped at LSS2 (assuming a median sediment size). This is an interesting result from a planning perspective, because LSS2 is only one dam of 14 expected to ultimately be sited on the Sre Pok and Se San Rivers. Upstream of LSS2, 13 reservoirs will trap sediment on the Se San and Sre Pok Rivers at an efficiency of 86%, but these reservoirs are only sited to receive 38% of the Se San and Sre Pok sediment loads. The suite of Cambodian dams on the Se San and Sre Pok Rivers, particularly LSS2 Dam, are poised to make a significant impact because their location and size would allow them to capture most of the sediment load transported by the two rivers. The more dams that are ultimately constructed in this planned Cambodian suite, the more difficult sediment management may become to conduct successfully, because the majority of sediment will be distributed in four reservoirs as opposed to just LSS2.

Referring again to Figure 2.4 and Figure 2.5a, reservoirs on the Sre Pok and Se San

Rivers may play an entirely different role in sediment trapping than reservoirs on the Se Kong River. Approximately 63% of the 3S basins sediment load (or 14.4 Mt y^{-1} out of 22.7 Mt y^{-1}) is assumed to be generated in the Sre Pok and Se San basins. The remaining 37% is generated in the Se Kong basin. In the DF and FD scenarios, the Se Kong basin would trap 20% and 47% of sediment generated in the Se Kong basin, which respectively represents 7% and 17% of sediment generated in total in the 3S basins. Figure 2.5a demonstrates the majority of Se Kong trapping occurs in three of the four reservoirs with the most storage capacity on the tributary: Xe Kong 4 (XK4), Xe Kong 5 (XK5) and Xekaman 1 (XK1). Conversely, in the DF and FD scenarios, 71% and 92% of sediment generated in the Sre Pok and Se San river basins is trapped, representing 45% and 58% of sediment generated in the entire 3S basins, respectively.

The significantly lower trapping in the Se Kong basin occurs despite the fact that the Se Kong basin is expected to host more dams (22 vs. 19) and only slightly less total storage capacity (25 billion m^3 vs. 27 billion m^3) than the Sre Pok and Se San Rivers combined, and (using the SV operating policy) produce over 42% of the 3S basins' mean annual energy. This occurs because Se Kong basin reservoirs are sited (or planned to be sited) at higher elevations within the sub-watershed with less contributing watershed area. While many of the Se Kong reservoirs will likely have very high sediment trapping efficiencies, they are sited such that they do not have the ability to trap as much of the sub-basin's sediment load. Of course, local geomorphological and ecological impacts downstream of the Se Kong dams could be severe given the high trapping efficiencies of the largest planned reservoirs, but the fact that less total load is expected to be trapped must be viewed as a benefit. If development plans in the Se Kong basin shift such that large dams are built on the main tributary and at lower elevations (such as what has occurred in the Sre Pok and Se San basins), 3S basins trapping may become critically high (greater than

90%).

Assuming all 3S basins dams are constructed, *Kummu et al.* [2010] report sub-basin sediment trapping in the Se Kong, Se San and Sre Pok Rivers to be 32%, 88% and 77%, respectively, compared to the values reported here (47%, 92% and 93%, respectively). The two sets of estimates are different because Kummu et al. (1) use different data to estimate trapping efficiencies, including different reservoir inflows and reservoir storage capacities; and (2) estimate sub-basin trapping efficiencies by lumping together the storage volumes of the reservoirs in each sub-basin, rather than by simulating the trapping that takes place in each reservoir.

3.3 Impacts on Storage Capacity

If protecting Mekong ecosystems is not adequate motivation for initiating sediment management practices, the potential for sedimentation to reduce storage capacity and ultimately energy production could serve as motivation. Figure 2.5b displays the percentage of initial total reservoir storage capacity (not just active storage capacity) that is lost after 100 years of simulated sediment accumulation in each 3S basins reservoir. Capacity loss error bars show the sensitivity of these losses to sediment loads, sediment size and basin development assumptions. For many reservoirs, these errors bars are too small to be visible. These results suggest that after 100 years of sedimentation, very few dams are likely to experience significant loss in total storage capacity. Despite the significant sediment production in the 3S basins, this result occurs because 3S basins reservoirs are expected to maintain 52.7 billion m^3 of storage capacity. Assuming a trapping efficiency of 100%, it would take about 2,750 years to lose 52.7 billion m^3 of capacity to 22.7 Mt y^{-1} (or about 19 million m^3 y^{-1}) of sedimentation.

In the DF scenario, only four dams experience a loss in initial total storage capacity of 20% or more for at least one of the sediment size assumptions: Lower Se San 2 (LSS2) (Cambodia, 400 MW), Buon Kuop (Vietnam, 280 MW), Sre Pok 3 (Vietnam, 220 MW), and Sre Pok 4 (Vietnam, 70 MW). In the FD scenario, only five dams are included on that list, with LSS2 being removed and Xe Kong 3D (Lao PDR) and Xekaman 4A (Lao PDR) being added to the list. Importantly, in the FD scenario, while the four large Cambodian reservoirs are expected to trap 48% of all sediment trapped in the 3S basins, they are not among the small subset of dams with significantly impacted storage capacity. Note that Lower Se San 2 (LSS2) is expected to trap less sediment in the FD scenario than the DF scenario because additional dams will be constructed upstream that will trap sediment and prevent it from reaching LSS2. Construction of more reservoirs simply distributes the basin's sediment load among more reservoirs, thereby further reducing sedimentation concerns at individual dams. Worldwide, storage capacity is being lost in reservoirs at a rate of 0.5%-1% per year [*Mahmood*, 1987; *White*, 2001]. The annual loss numbers in the 3S basins are much lower, given that only five reservoirs are losing capacity at a rate greater than 0.2% per year, and only one reservoir falls into the 0.5%-1% category.

The error bars surrounding each plotted point in Figure 2.5b demonstrates that for most reservoirs there is not much difference in the system's overall storage capacity loss for different sediment size and basin development assumptions. However, at the five reservoirs expected to experience the largest loss in storage capacity, there is significant uncertainty regarding the estimates at these sites. For example, at LSS2, whether or not five planned Cambodian dams are built upstream creates significant uncertainty regarding potential sediment trapping and thus storage capacity loss. In comparing Figure 2.5a to Figure 2.5b, it is clear that the reservoirs expected to trap the most sediment (Cambodian reservoirs LSS2, Lower Se San 3, Lower Sre

Pok 3, and Lower Sre Pok 4) are generally not the reservoirs expected to experience the largest loss in storage capacity. Additionally, reservoirs with large initial storage capacities generally experience less significant reductions in storage capacity from sedimentation compared to smaller reservoirs.

There is minor additional sensitivity analysis that can be performed on the storage capacity loss estimates. First, the 22.7 Mt y^{-1} estimate is already at the upper end of the 10-25 Mt y^{-1} estimate offered by other researchers, so experimenting with the magnitude of sediment yield (t km^{-2} yr^{-1}) in this study will not significantly increase storage capacity losses. Decreasing the bulk density of sediment deposits from 1200 kg/m^3 to 1100 kg/m^3 only increases sedimentation volume by about 8%. Thus, a reservoir with a 20% loss in storage capacity instead experiences a loss of 21.6%. A similarly insignificant result occurs when accounting for bedload by increasing sediment inflows to each reservoir site by 10% and trapping 100% of that additional sediment.

3.4 Sediment Management Implications

Reservoir sediment management requires a variety of expenses, such as the installation of low and mid-level outlets in a dam. These costs may be much more manageable if sediment management facilities are included in the dam when it is constructed, rather than retrofitting such facilities into dams that have already been built [*Palmieri et al.*, 2003]. Unfortunately, almost half of the 3S basins dams have already been constructed, mostly without sediment management facilities in place. Whether sediment management will be economically feasible at such sites remains to be determined, but there does still exist ample opportunity to manage sediment at dams in the 3S basins that have not yet been constructed. This may require changes to the location, design, and operating policies of these dams [*Annandale* 2012a, 2012b, 2012c; *Wild* *and Loucks*, 2013, 2014a].

For example, significant trapping is predicted at the planned Cambodian dams in the Sre Pok and Se San basins, primarily Lower Se San 2 and Lower Se San 3 (on the Se San River), and Lower Sre Pok 3 and Lower Sre Pok 4 (on the Sre Pok River). In the FD scenario, assuming median sediment size for sediment trapping, these four reservoirs are predicted to trap 37% of the 3S basins' sediment load, which is about 48% of the expected trapping in all 3S basins reservoirs. Furthermore, these dams are sited at the bottom of the Se San and Sre Pok Rivers, so they control the potential impact that any upstream efforts (particularly in Vietnam) could have on the system's sediment discharge into the Mekong River. Despite this high trapping, there is not an obvious opportunity to reduce sedimentation without adversely impacting short-term energy production. Unlike Lao PDR and Vietnam, Cambodia is located such that it is not possible to reduce trapping by producing energy at higher elevations in the 3S basins where reservoirs receive lower sediment inflows. Decision makers in Cambodia may wish to consider sediment management options for their planned 3S basins dams given the potential consequences of downstream sediment starvation, but such changes may increase dam costs and reduce short-term hydropower benefits. Sediment management at the proposed cascade of dams on the upper Se Kong River, including Xe Kong 5 and Xe Kong 4 (as well as Xe Kong 3U and Xe Kong 3D, which are just downstream and therefore ultimately control the impact of measures taken at Xe Kong 5 and Xe Kong 4), would also benefit the basin's sediment balance, as 8% of 3S basins' load may be trapped there in the FD scenario.

The situation is more difficult in Vietnam, where dam building is mostly completed in the 3S basins, making sediment management more costly and less likely. Furthermore, taking measures to manage sediment will have no impact if the downstream dams in Cambodia do not have sediment management capabilities. The fact that two countries are involved adds to the challenge of making this work. Even in the Se Kong basin, where dams are only in Lao PDR, different dam owners and operators may have conflicting goals.

Losing 20% of storage capacity in 100 years may not concern individual dam owners and operators enough to take measures to reduce sedimentation. However, without detailed dam specifications and reservoir operating policies, it is very difficult to make generalizations about the point at which 3S basins dams' functionality and profitability are significantly compromised by sedimentation. For example, reservoirs with hydropower outlets at lower elevations may become affected more quickly than those with higher level outlets. Additionally, the extent to which a reservoir's active storage capacity (and therefore energy production) is impacted over time depends on reservoir geometry, operations, and sediment grain size. Reservoirs designed to perform significant intra- or inter-annual carry over storage, or attenuate flood peaks, may be more seriously impacted than run-of-river dams that do not rely on large active storage capacities. Still, the results of simulations with *SedSim* do not suggest that sedimentation will be severe enough to inspire changes to the current dam design and planning process, particularly because distant sedimentation-related costs are effectively absent from traditional economic analyses. In order to understand the likelihood that sediment management practices ultimately take place, it is important to clarify who benefits from these dams, and when.

In many cases, the national governments of LMB countries are entering into agreements with foreign investors that build, own, and operate the dams for up to 40 years, after which the investors transfer the dam to the national government (BOOT agreements). Our simulations show sedimentation is not likely to have an impact on storage capacity and operations (and therefore profits) on such a short time scale, so the short-term owners and operators will likely have no interest in sediment management. In such circumstances, it is the eventual owners and operators (the national governments of Lao PDR, Cambodia and Vietnam) that may be persuaded to conduct sediment management, because they are more likely to make management decisions that reflect the long term interests of their respective countries. The national governments have the authority to require that new dams be constructed with sediment management facilities in place, although this might result in associated costs being passed on to power customers.

For decision makers to view sediment management as an economic benefit, the traditional paradigm of economic analysis must be modified in at least two ways. First, the benefits of sediment management must include environmental benefits, especially those related to the valuable Mekong fishery. This alone is likely enough to suggest sediment management is economically beneficial, given the multi-billion dollar annual valuation of the Mekong fishery, and its importance to food security [*MRC*, 2010]. Second, the costs and horizon of the economic analysis must account for the fact that sedimentation can result in significant costs to recover silted out reservoir sites for use by future generations [*Morris and Fan*, 1998; Palmieri et al., 2003; *Annandale*, 2013].

Without any sediment management, eventually 3S basins dams will fill with sediment, unless their structural integrity is compromised. Whichever comes first, significant quantities of sediment will be stored behind the dams, and the dams can either be left in place to eventually become a safety hazard, or can be removed. If the defunct dam is left in place, the economic and political costs associated with potential failure are substantial, and future generations are denied the opportunity to benefit from a viable reservoir site, of which there are a limited number. On the other hand, removal of the dam may prove to be prohibitively costly in the absence of a retirement fund established by the original dam owners [*Palmieri et al.*, 2003]. Furthermore, to restore the viability of the reservoir site for future use in an environmentally conscious manner may require extremely costly management of the immense quantity of sediment deposited at the site [*Morris and Fan*, 1998]. Again, 100 years of sedimentation without sediment management could require management of more than 1 billion m^3 of sediment in the 3S basins, all by future generations. Either way, the absence of sediment management is unequivocally unsustainable because it neglects the importance of intergenerational equity [*Annandale*, 2013].

4 Conclusions and Recommendations

More than 50% of sediment flux in regulated river basins worldwide may be getting trapped in reservoirs or other artificial impoundments [*Vörösmarty et al.*, 2003]. The Sre Pok, Se San and Se Kong (3S) River basins are no exception. Results of simulations suggest that about 40%-80% of the suspended sediment load could be trapped in 3S basins reservoirs, depending especially upon the number of reservoirs that will be located, designed and operated, and to a lesser extent the type and size of sediment produced (and therefore the efficiency with which sediment is likely to be trapped). This sediment starvation due to reservoir trapping could have a significant impact on critical Mekong ecosystems, such as Cambodia's Tonle Sap Lake and the Vietnam Delta. These two critical ecosystems provide food and economic security for tens of millions of people.

Ample opportunities exist in the 3S basins to generate hydroelectric energy without extreme sediment starvation. We identified particular sediment management opportunities at four planned Cambodian dams, including Lower Se San 2, as well as at several planned dams on the Se Kong tributary in Lao PDR, including Xe Kong 5 and Xe Kong 4. LMB decision-makers may wish to consider requiring dams to be designed now with sediment management facilities in place, such as low- and mid-level outlets, as many sediment management techniques may become too difficult and expensive to retrofit (e.g., as would be required at most 3S basins dams in Vietnam). However, convincing dam owners and operators to conduct sediment management practices may be difficult given their short-term interest in generating profit. Managing sediment requires investing in infrastructure, and possibly changing the siting, design and operating policies of dams, all of which carry costs. Additionally, our simulation results demonstrate that 100-year storage capacity losses exceed 20% in only five reservoirs in the full development scenario, without significant variation showing up in the sensitivity analysis. Thus, for sediment management to be deemed economically beneficial, the governments of LMB countries, the likely long-term owners and operators of hydropower dams, will need to consider the costs of inaction, particularly with regard to ecosystem services such as food production and food security. Decision makers may also have to grapple with the relative importance of intergenerational equity, as inaction may result in enormous costs being imposed on future generations to decommission dams and somehow manage the accumulated sediments.

Even if LMB governments decide that sediment management is important, it may be particularly difficult to do. In heavily developed international sub-basins such as the 3Ss, sediment management may only be effective if sediment is passed through cascades of dams in a coordinated manner. However, if success is achieved, the lessons learned in the 3S basins would serve as a learning opportunity not only for the rest of the Mekong basin, but for other sediment-laden river basins that may face similar challenges now and in the future.

Future work should first confirm or reject previous assessments of the physical feasibility of various sediment management techniques at dams in the 3S basins [*Annandale* 2012a, 2012b 2012c]. Additionally, the economic feasibility of sediment management at potentially impactful sites must be assessed, including mechanisms to distribute the associated costs among investors, power customers, and those dependent on the productive Mekong fisheries. If these sediment management techniques are feasible, future work should build upon previous assessments of the potential effectiveness of these techniques and their impacts on energy production [*Wild and Loucks,* 2013, 2014a]. Second, these future assessments of specific sediment management techniques, as well as simulations with more detailed sediment transport models, will benefit from improved data sets. For example, these data include spatially distributed sediment sampling in the 3S basins (including grain size distributions and bedload estimates), which would improve estimates of sediment production and trapping. Also, detailed reservoir operating policies, improved total storage estimates, and sedimentation records at existing sites would enable improved prediction of both sediment trapping and impacts on storage capacity and reservoir operations. Third, future work must include better understanding the interactions among sediment, nutrients and aquatic species in the Mekong basin. Until these interactions are better understood, it is difficult to estimate the true economic and ecological benefit of sediment management.

5 References

Adamson, P.T., I.D. Rutherford, M. C. Peel, and I.A. Conlan (2009), The Hydrology of the Mekong River, in *The Mekong: Biophysical Environment of an International River Basin*, edited by I.C. Campbell, pp.53-76, Elsevier, Amsterdam.

Annandale, G.W. (2012a), *A Climate Resilient Mekong: Sediment Pass-Through at Lower Se San 2*, Golder Assoc. Inc., Lakewood, CO, Nat. Heritage Inst., San Francisco, Calif.

Annandale, G.W. (2012b), *A Climate Resilient Mekong: Sediment Pass-Through at Sambor Dam*, Golder Assoc. Inc., Lakewood, CO, Nat. Heritage Inst., San Francisco, Calif.

Annandale, G.W. (2012c), *A Climate Resilient Mekong: Maintaining the Flows that Nourish Life: Maximizing Sediment Passage through Dams on the Xe Kong River, Laos*, Golder Assoc. Inc., Lakewood, CO, Nat. Heritage Inst., San Francisco, Calif.

Annandale, G.W. (2013), *Quenching the Thirst: Sustainable Water Supply and Climate Change,* CreateSpace, North Charleston, S. C.

Baran E., and E. Guerin (2012), *Fish bioecology in relation to sediments in the Mekong and in tropical rivers*, Report for the Project “A Climate Resilient Mekong: Maintaining the Flows that Nourish Life” led by the Nat. Heritage Inst., WorldFish Cent., Phnom Penh, Cambodia, 52.

Baran, E., S. Samadee, T.S. Jiau, and T.T. Cong (2013), *Fish and fisheries in the Sekong, Sesan and Srepok basins (3S Rivers, Mekong Watershed), with special reference to the Sesan River*, Water and Food Challenge Program in the Mekong, Optimizing the management of a cascade of reservoirs at the catchment level, WorldFish Center, Phnom Penh, Cambodia, 65.

Brandt, S.A. (2000), Classification of geomorphological effects downstream of dams, *Catena,* 40, 375-401.

Brune, G.M. (1953), Trap Efficiency of Reservoirs, *Trans. AGU,* 34, 407-418.

Churchill, M.A. (1948), Discussion of paper by L.C. Gottschalk, Analysis of Use of Reservoir Sedimentation Data, in *Proceedings of the Federal Inter-Agency Sedimentation Conference*, Denver, CO, 139-140.

Clift, P.D., D.L. Graham, and J. Blusztajn (2004), Marine sedimentary evidence for monsoon strengthening, Tibetan uplift and drainage evolution in East Asia, in *Continent and Ocean Interactions with East Asian Marginal Seas*, *Geophys. Monogr. Ser.* 149, pp. 259–282, AGU, Washington, D. C.

Fu, K.D., and D.M. He (2007), Analysis and prediction of sediment trapping efficiencies of the reservoirs in the mainstream of the Lancang River, *Chin. Sci. Bull.,* 52(Supp. II), 134–140.

Grant, G.E. (2012), The Geomorphic Response of Gravel-bed Rivers to Dams: Perspectives and Prospects, in *Gravel-bed Rivers: Processes, Tools, Environments,* edited by M. Church, et al., Wiley.

Grant, G.E., J.C. Schmidt, and S.L. Lewis (2003), A geological framework for interpreting downstream effects of dams on rivers, in *A Peculiar River*, *Water Sci. Appl.*, vol. 7, edited by J.E. O'Connor and G.E. Grant, pp. 203-219, AGU, Washington, D. C.

Grumbine, E.R., J. Dore, and J. Xu (2012), Mekong hydropower: drivers of change and governance challenges, *Front. Ecol. Environ*., 10(2), 91-98, doi: 10.1890/110146.

Gupta, A., and S.C. Liew (2007), The Mekong from satellite imagery: a quick look at a large river, *Geomorphology*, 85, 259-274.

Halls, A.S., I. Conlan, W. Wisesjindawat, K. Phouthavongs, S. Viravong, S. Chan, and V.A. Vu (2013), Atlas of deep pools in the Lower Mekong River and some of its tributaries, *MRC Tech. Pap. 31*, Mekong River Comm., Phnom Penh, Cambodia, 69.

Hirsch, P. (2010), The changing political dynamics of dam building on the Mekong, *Water Alternatives*, 3(2), 312-323.

Hortle, K.G. (2009), Fishes of the Mekong - how many species are there? *Catch and Culture,* 15, 4-12.

ICEM (2010), Hydrology and Sediment Baseline Assessment Working Paper, in *Baseline assessment report, Strategic Environmental Assessment of hydropower on the Mekong mainstream for the MRC*, pp. 85, Int. Cent. Environ. Manage., Hanoi, Vietnam.

Johnston, R., and M. Kummu (2012), Water Resource Models in the Mekong Basin: A Review, *Wat. Resour. Manage.*, 26, 429-455.

Junk, W. J., P.B. Bayley, and R.E. Sparks (1989), The flood pulse concept in river-floodplain systems, in *Proceedings of the International Large River Symposium (LARS), Can. Spec. Publ. Fish. Aquat. Sci.*, edited by D. P. Dodge, pp. 110–127.

Kondolf, G.M. (1997), Hungry water: Effects of dams and gravel mining on river channels, *Environ. Manage.*, 21(4), 533-551.

Kondolf, G.M., C. Alford, and Z. Rubin (2011), *Cumulative Effects of Tributary Dams on the Sediment Loads and Channel Form in the Lower Mekong River: Progress Report through 30 September 2011*, Dep. of Landscape Archit. and Environ. Plann., Univ. of California, Berkeley.

Kondolf G.M., Z. Rubin, C. Alford, J.T. Minear (2013), Cumulative sediment reduction to the lower Mekong River from planned dams, In Fukuoka S, Nakagawa H, Sumi T, Zhang H (eds), *Advances in River Sediment Research*, London, UK, Taylor and Francis.

Kummu, M., and O. Varis (2007), Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River, *Geomorphology*, 85, 275-293.

Kummu, M., X.X. Lu, J.J. Wang, and O. Varis (2010), Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong, *Geomorphology*, 119, 181–197.

Lamberts, D. (2006), The Tonle Sap Lake as a productive ecosystem, *Int. J. Water Resour. Dev.*, 22(3), 481-495.

Lara, J.M., and E.L. Pemberton (1963), Initial Unit Weight of Deposited Sediments, in *Proceedings of Federal Interagency Sedimentation Conference, USDA-ARS Misc. Publ. 970*, pp. 818-845.

Lewis, S. E., Z. T. Bainbridge, P. M. Kuhnert, B. S. Sherman, B. Henderson, C. Dougall, M. Cooper, and J. E. Brodie (2013), Calculating sediment trapping efficiencies for reservoirs in tropical settings: A case study from the Burdekin Falls Dam, NE Australia, *Water Resour. Res.*, 49, 1017-1029, doi:10.1002/wrcr.20117.

Lu, X.X., and R.Y. Siew (2006), Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams, *Hydrol. Earth Syst. Sci.,* 10, 181–195.

Mahmood, K. (1987), Reservoir Sedimentation: Impact, Extent, Mitigation, *World Bank Tech. Rep. 71*, Washington, D.C.

Mekong River Commission (MRC) (2005), *Overview of the Hydrology of the Mekong Basin*, Mekong River Comm., Vientiane, November 2005, 73.

Mekong River Commission (MRC) (2009), *The flow of the Mekong, MRC Management Information Booklet Ser. 2*, Mekong River Comm., Vientiane, November 2009, 12.

Mekong River Commission (MRC) (2010), *State of the Basin Report*, Mekong River Comm., Vientiane, 2010.

Mekong River Commission (MRC) (2011a), *Application of MRC Modelling Tools in the 3S basin*, Mekong River Comm., Vientiane, 2011.

Mekong River Commission (MRC) (2011b), *Basin Development Plan Programme Phase 2: Assessment of Basin-wide Development Scenarios*, Main Rep., Mekong River Comm., Vientiane, April 2011.

Mekong River Commission (MRC) (2012), *Hydropower Project Database*, Basin Development Plan Programme, Mekong River Comm., Vientiane, Lao PDR.

Milliman, J.D., and R.H. Meade (1983), World-wide delivery of river sediment to the oceans, *Geology*, 91, 1-21.

Minear, T., and G.M. Kondolf (2009), Estimating reservoir sedimentation rates at large spatial- and temporal-scales: a case study of California, *Water Resour. Res.,* 45, W12502, doi:10.1029/2007WR006703.

Morehead, M.D., J.P. Syvitski, E.W.H. Hutton, and S.D. Peckham (2003), Modeling the temporal variability in the flux of sediment from ungaged river basins, *Global Planet. Change*, 39(1-2), 95-110.

Morris, G.L., and J. Fan (1998), *Reservoir Sedimentation Handbook*, McGraw Hill, New York.

Palmieri A., F. Shah, G.W. Annandale, and A. Dinar (2003), *Reservoir Conservation Volume I: the RESCON Approach*, economic and engineering evaluation of alternative strategies for managing sedimentation in storage reservoirs, A contribution to promote conservation of water storage assets worldwide, Int. Bank for Reconstruction and Dev./The World Bank, Washington, D.C., 101.

Petts, G.E., and A.M. Gurnell (2005), Dams and geomorphology: research progress and future directions, *Geomorphology,* 71, 27-47.

Piman, T., T. Cochrane, M. Arias, A. Green, and N. Dat (2013), Assessment of Flow Changes from Hydropower Development and Operations in Sekong, Sesan and Srepok Rivers of the Mekong Basin, *Water Resour. Plann. Manage.*, 139(6), 723-732.

Piman, T., T. Cochrane, M. Arias, N. Dat, and O. Vonnarart (2014), Managing Hydropower under Climate Change in the Mekong Tributaries, in *Managing Water Resources Under Climate Uncertainty: Opportunities and Challenges*, edited by S. Shrestha, Springer.

Power, M.E., W.E. Dietrich, and J.C. Finlay (1996), Dams and Downstream Aquatic Biodiversity: Potential Food Web Consequences of Hydrologic and Geomorphic Change, *Environ. Manage.,* 20(6), 887-895.

Power Engineering Consulting Joint Stock Company (PECC1) (2013), *Sediment Report prepared for Natural Heritage Institute (NHI)*, Hanoi City, Vietnam, 29.

Sarkkula, J., J. Koponen, H. Lauri, and M. Virtanen (2010), *Mekong River Commission (MRC) Detailed Modelling Support (DMS) Project - Origin, fate and impacts of the Mekong sediments*, 53.

Schmidt, J.C., and P.R. Wilcock (2008), Metrics for assessing the downstream impacts of dams, *Water Resour. Res.,* 44, W04404, doi:10.1029/2006WR005092.

Sverdrup-Jensen, S. (2002), Fisheries in the Lower Mekong Basin: Status and Perspectives, *MRC Tech. Pap. 6*, Mekong River Comm., Phnom Penh, 103.

Ta, K.T.O., V.L. Nguyen, M. Tateishio, I. Kobayashi, S. Tanabe, and Y. Saito (2002), Holocene delta evolution and sediment discharge of the Mekong River, Southern Vietnam, *Quat. Sci. Rev.,* 21, 1807–1819.

Turowski, J.M., D. Rickenmann, and S.J. Dadson (2010), The partitioning of the total sediment load of a river into suspended load and bedload: a review of empirical data, *Sedimentology,* 57, 1126-1146.

Ty, T.V., K. Sunada, and Y. Ichikawa (2011), A spatial impact assessment of human-induced intervention on hydrological regimes: a case study in the upper Srepok River basin, Central Highlands of Vietnam, *Int. J. of River Basin Manage.*, 9(2), 103-116.

Ty, T.V., K. Sunada, and Y. Ichikawa (2012), Water resources management under future development and climate change impacts in the Upper Srepok River Basin, Central Highlands of Vietnam, *Water Policy*, 14, 725-745.

Vörösmarty, C.J., M. Meybeck, B. Fekete, K. Sharma, P. Green, and J.P.M. Syvitski (2003), Anthropogenic sediment retention: major global impact from registered river impoundments, *Global Planet. Change*, 39(1–2), 169–190.

Walling, D. (2005), *Analysis and evaluation of sediment data from the Lower Mekong River*, Report submitted to the Mekong River Comm., Dep. of Geogr., Univ. of Exeter.

Walling, D.E. (2008), The changing sediment load of the Mekong River, *Ambio,* 37(3), 150–157.

Walling, D.E. (2009), *The Impact of Global Change on Erosion and Sediment Transport by Rivers*, UNESCO, Paris.

Wang, J.J., X.X. Lu, and M. Kummu (2011), Sediment load estimates and variations in the Lower Mekong River, *Riv. Res. Appl.*, 27, 33-46.

White, W. R. (2001), *Evacuation of Sediments from Reservoirs*, Thomas Telford, London.

Wild, T.B., and D.P. Loucks (2012a), Assessing the Potential Sediment-Related Impacts of Hydropower Development in the Mekong River Basin, in *Proceedings of the ASCE World Environmental and Water Resources Congress 2012*, Albuquerque, N.M., pp. 2236-2246.

Wild, T.B., and D.P. Loucks (2012b), *SedSim Model: A Simulation Model for the Preliminary Screening of Sediment Transport and Management in River Basins, Version 3.0: Documentation and User's Manual*, Dep. of Civ. and Environ. Eng., Cornell Univ., Ithaca, New York.

Wild, T.B., and D.P. Loucks (2013), Managing Sediment in the Mekong River Basin: Tradeoffs Between Hydropower and the Environment, in *Proceedings of the ASCE World Environmental and Water Resources Congress 2013*, Cincinnati, Ohio, pp. 1297-1307.

Wild, T.B., and D.P. Loucks (2014a), Mitigating Dam Conflicts in the Mekong River Basin, in *Conflict Resolution in Water Resources and Environmental Management*, edited by K.W. Hipel, et al., Springer, Heidelberg, accepted with minor revisions.

Wild, T.B., and D.P. Loucks (2014b), Managing the Impacts of Reservoirs in the Mekong River Basin, in *Proceedings of the ASCE World Environmental and Water Resources Congress 2014*, Portland, OR, pp. 1070-1080.

Wisser, D., S. Frolking, S. Hagen, and M. F. P. Bierkens (2013), Beyond peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs, *Water Resour. Res., 49*, 5732–5739, doi:10.1002/wrcr.20452.

Xue, Z., J.P. Liu, D. DeMaster, L.V. Nguyen, and T.K.O Ta (2010), Late Holocene Evolution of the Mekong Subaqueous Delta, Southern Vietnam, *Mar. Geol.*, 269, 45-60.

CHAPTER 3

MANAGING THE IMPACTS OF RESERVOIRS IN THE MEKONG RIVER BASIN: TRADEOFFS BETWEEN HYDROPOWER AND THE ENVIRONMENT

Abstract

Hydropower dams are being constructed at a rapid pace in the Mekong/Lancang River basin. The river and its tributaries transport nearly 160 million metric tons of sediment per year to the South China Sea, but reservoirs are expected to trap significant fractions of this sediment, rendering much of it unavailable to support ecosystem productivity and maintain the river's geomorphology. We introduce and apply a methodology for evaluating the potential effects of sediment-focused changes to the planned siting, design and operating policies of dams on the natural sediment regime, as well as on hydropower production and reliability. This approach is applied to the proposed Lower Se San 2 Dam in Cambodia, which would span across the confluence of the Sre Pok and Se San tributaries to the Mekong, thereby preventing a significant source of sediment from reaching critical Mekong ecosystems such as Cambodia's Tonle Sap Lake and the Vietnam Delta. Simulation results suggest that various changes to the reservoir's location, design and operating policy could increase sediment discharge from this site by 300-450% compared to current plans, but that a 30-55% loss in annual energy production may be necessary to achieve the improved sediment passage. Simulation results also suggest that sediment management-focused reservoir operating policies could cause ecological damage if they are not designed in ways that do not adversely impact the ecology.

1 Introduction

Originating in the Tibetan Plateau, the Mekong River flows some 4750 km, passing through the Upper Mekong Basin in China (where it is called the Lancang Jiang) and Myanmar before entering the Lower Mekong Basin (LMB) in Thailand, Lao PDR, Cambodia and Vietnam. The river's watershed covers about 800 thousand km^2, producing a mean annual runoff of 15,000 m^3/s. Recently, the absence of military conflict and regional growth in energy demand, among other factors, have contributed to an increased interest in hydropower development. The LMB has an estimated hydropower potential of 30,000 MW, of which only 10% has been developed [*Mekong River Commission (MRC)*, 2010]. By 2030, 62 dams are expected to be completed, including 6 on the Lancang River and 56 on LMB tributaries [*MRC*, 2011b]. In the long term, plans exist for 134 dams to be constructed in the LMB.

This untapped hydropower potential represents an opportunity for LMB countries to significantly alter the development paths of their respective countries, particularly in Lao PDR and Cambodia, where rapid economic development is internally viewed as a necessity in order to achieve their Millennium Development Goals [*MRC*, 2010]. Hydropower is a particularly attractive energy option in LMB countries because water is abundant and renewable, can be generated domestically, and is potentially more environmentally friendly than other options (e.g., coal). In addition to increasing energy supply for domestic consumption, hydropower energy can be exported for significant profit, particularly in Lao PDR and Cambodia, where hydropower potential exceeds national demand, and exports will be sold primarily to China, Thailand and Vietnam.

Despite the potential benefits of energy production, decision makers are facing an extremely difficult challenge in balancing energy production goals with the competing objective of maintaining the river basin's exceptional productivity and biodiversity. Hydropower dams that alter the natural sediment and flow regimes threaten valuable Mekong ecosystems. The Mekong basin's fishery has been valued at between 2-7 billion USD per year. People living in the LMB are heavily dependent on this productivity for food security and income, with fish and other aquatic animals providing between 47% and 80% of the protein consumed (depending on the country) and providing employment for over 60% of the economically active population. The river's biodiversity is second only to the Amazon River basin, and is home to approximately 20,000 plant, 430 mammal, 1200 bird, 800 reptile and amphibian [*MRC*, 2010], and 850 fish species [*Hortle*, 2009]. Each country's fate will be determined in part by the decisions taken with respect to these tradeoffs between hydropower and the environment.

The driver of the basin's productivity and biodiversity is the annual flood pulse, which transports most of the annual sediment and nutrient loads and encourages the exchange of water, sediment and nutrients between the river and its floodplains [*Junk*, 1989; *Sverdrup-Jensen*, 2002; *Lamberts*, 2006]. Sediment plays an important role in nutrient transport [*Baran and Guerin,* 2012], and controls the geomorphology of the river basin, which creates important physical features and habitats that contribute to the river's productivity. The river produces approximately 160 million metric tons (Mt) of suspended sediment per year [*Milliman and Meade*, 1983]. Approximately half of this load is generated in the Upper Mekong Basin in China [*Gupta and Liew*, 2007; *Walling*, 2008], while the remaining half is produced in the LMB [*Clift et al.*, 2004]. Dams in China are expected to trap most of the 80 Mt generated annually there [*Lu and Siew*, 2006; *Fu and He*, 2007; *Kummu and Varis*, 2007; *Kondolf et al.*, 2014], while the extent of trapping throughout the LMB is potentially significant, and will depend on the number of reservoirs that are ultimately built [*Kummu et al.*, 2010; *Kondolf et al.*, 2014].

Three of the biggest contributors of flow and sediment to the mainstream Mekong River are the Sre Pok, Se San and Se Kong (3S) tributary Rivers (see Figure 3.1). The 3S tributaries, which have a combined contributing watershed area of approximately 78,650 km^2, almost equally divided among Cambodia, Lao PDR and Viet Nam, produce a combined annual discharge of about 17%-20% of the Mekong River's flow and 5%-15% of its sediment (10-30% of LMB sediment production) [*Kondolf et al.*, 2011; *Sarkkula et al.*, 2010; *ICEM*, 2010]. *Wild and Loucks* [2014a] demonstrated that the 18 existing and 21 planned 3S basins reservoirs, which will provide 6600 MW of installed hydropower capacity, have the potential to trap 40%-80% of 3S basins sediment load, depending on how many reservoirs are ultimately built and assumptions regarding sediment size. Without any reservoir sediment management, trapping in 3S basins reservoirs could reduce mainstream Mekong sediment loads by as much as 7%-31%, depending on how many reservoirs are ultimately constructed throughout the LMB. The 3S rivers provide the last large source of sediment and water flows to two critically important Mekong ecosystems: the Vietnam Delta and Cambodia's Tonle Sap Lake (the most productive freshwater fishery in the world). Additionally, the 3S basins are home to over 40% of the total Mekong fish biodiversity (329 fish species), including 17 fish species found nowhere else in the world [*Baran et al.*, 2013], and provide critical fish spawning and breeding grounds.

This study has two primary purposes. First, we propose a methodology for assessing the effectiveness of various multiple reservoir sediment management practices, including changes to the siting, design and operating policies of planned dams. This methodology was developed for

Figure 3.1: Se San, Sre Pok, and Se Kong (3S) tributary basins to the Mekong River, showing existing and proposed hydropower dams[2]. Based on data from *MRC* [2012]. The focus of this study is Lower Se San 2 Dam, which is listed as Lower Se San + Sre Pok 2 in the figure.

---

[2] This figure is reproduced with permission from John Wiley and Sons: Wild, T.B., and Loucks, D.P. (2014), *Water Resour. Res.,* 50, 5141-5157, DOI: 10.1002/2014WR015457.

use by various water resources-related ministries in LMB countries to identify the tradeoffs between sediment passage and the energy production and reliability that may accompany sediment-focused changes in dam siting, design and operation, including the sensitivity of these tradeoffs to various assumptions and parameter values. The Mekong River Commission has noted in its dam design guidance documentation [*MRC*, 2009a] the potential for techniques such as sediment flushing to improve sediment passage at dams in the Mekong basin. This paper introduces a simple approach to evaluate the potential impacts of such approaches on multiple reservoir systems. The approach presented here may serve as a useful template for other researchers to conduct similar analyses in the future throughout the Mekong basin (or in other river basins facing similar rapid development concerns), particularly because new data and dam plans continue to become available.

Second, we apply this methodology to evaluate alternative strategies to improve sediment passage at one proposed, and potentially severely impactful [*Wild and Loucks*, 2014a], dam in the Mekong Basin: Lower Se San 2 Dam in Cambodia, as indicated in Figure 3.1. It is critical to identify potentially effective sediment management measures at dams that have not yet been constructed, as it may be difficult and expensive to retrofit existing dams with sediment management facilities [*Kondolf et al.*, 2014]. The LSS2 Dam, with a planned installed capacity of 400 MW and total storage capacity of 1,793 10^6 m^3, would straddle the confluence of the Se San and Sre Pok Rivers, controlling the rivers' discharge of flow and sediment into the Mekong River and its important ecosystems such as the Vietnam Delta and Cambodia's Tonle Sap Lake. The dam alone could reduce basin-wide fish biomass production by over 9 percent [*Ziv et al.*, 2012], which is the highest potential among tributary dams. Given its location downstream of 18 other existing and proposed dams on the Sre Pok and Se San Rivers, the absence of sediment management facilities at LSS2 could discourage any efforts to manage sediment at upstream dams. Preliminary site work has already started at LSS2, and the dam could begin commercial operations by 2017 if the Cambodian National Government proceeds with the current design. (Unlike the process for mainstream Mekong River dams, no “prior consultation” with other countries sharing the Mekong River is required for a tributary dam such as LSS2). For all of these reasons, identification and evaluation of opportunities to increase sediment passage through the reservoir, while maintaining significant energy production at the site, is of current interest.

Rather than arguing no dams should be built, which is the best way to reduce sedimentation at reservoir sites, this study acknowledges that dams will be built, but suggests that, with regard to sediment, more benign alternatives to the currently proposed dams exist, and the National governments of LMB countries may wish to consider them. *Annandale* [2012] has conducted a preliminary evaluation of site conditions at the proposed LSS2 Dam, and has suggested various approaches to increase sediment discharge, while *Wild and Loucks* [2014b] performed preliminary evaluations of these approaches at LSS2. In this paper we build on these previous studies by proposing and evaluating the effectiveness of various sediment management-focused operating policies (e.g., sediment flushing and sediment routing) at alternative dams (with siting and design changes), their impact on energy production, and the sensitivity of these tradeoffs to various assumptions.

2 Overview of Available Sediment Management Techniques

We propose that alternative reservoir siting, design and operational strategies could improve sediment passage at Lower Se San 2 Dam. However, before introducing the particular strategies that we propose for LSS2, namely sediment flushing and sediment routing, it will be of value to discuss the range of reservoir sediment management techniques that are available, which generally fall into three categories: minimizing sediment inflow (e.g., catchment management), preventing inflowing sediment from depositing by hydraulically routing sediment beyond the reservoir (sediment routing), and removing sediment after it has deposited (sediment removal) [*Morris and Fan*, 1998]. This study will focus on the practices of sediment removal and routing, rather than on catchment management. Catchment management refers to sediment reduction practices such as re-vegetation. Currently in the Mekong Basin, the goal is to preserve the basin's ability to transport its naturally high sediment yield, rather than to reduce sediment loads.

Sediment removal is performed in two primary ways: direct removal (e.g., dredging), which entails the use of mechanical equipment to remove sediment from the reservoir, and flushing, which uses inflowing water to remobilize and remove sediment that has been previously deposited in the reservoir [*Atkinson*, 1996]. Flushing is the focus of this study, and it can be done in two ways: (1) partial drawdown flushing (also referred to as "pressure" flushing), or (2) full drawdown flushing, which is depicted in Figure 3.2 [*Atkinson*, 1996; *White*, 2001; *Palmieri et al.*, 2003]. Only full drawdown flushing is considered in this study because it is considerably more effective at removing deposited sediment than pressure flushing, which attempts to conduct flushing without draining the reservoir. During drawdown flushing, mid- and low-level outlets are used to empty the reservoir and maintain free-flow conditions for a short period of time during which inflowing water scours previously deposited sediment from the reservoir bed. Drawdown flushing has been practiced with success at numerous reservoirs throughout the world, successful examples of which include: Cachi Dam in Costa Rica [*Jansson and Erlingsson*, 2000], Unazuki and Dashidaira dams in Japan [*Kokubo et al.*, 1997; *Liu et al.*, 2004; *Sumi and Kanazawa*, 2006], Gebidem Dam in Switzerland, Sefid-Rud Dam in Iran, Sanmenxia Dam in China [*Wang et al.*, 2005], and the Genissiat Dam in France.

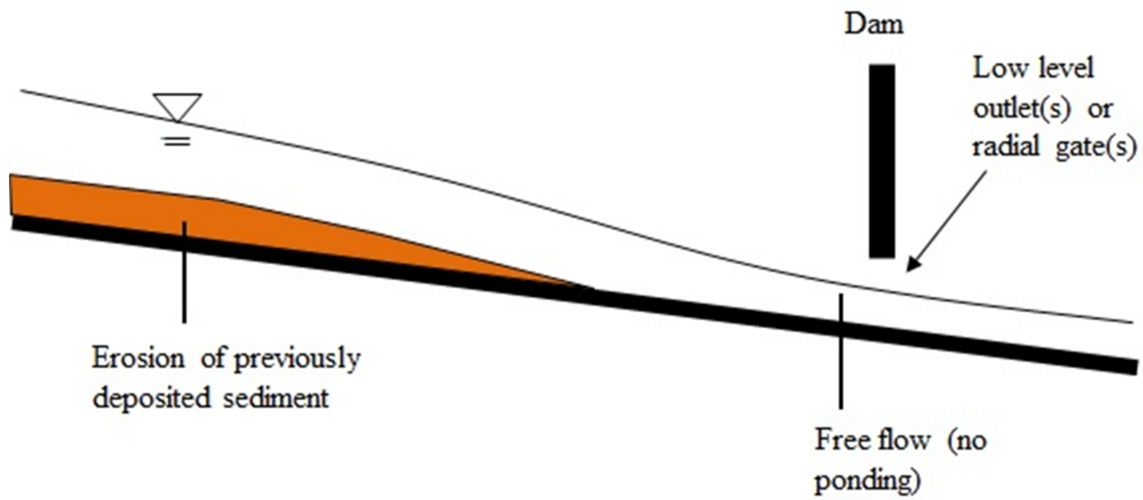


Figure 3.2: A schematic diagram of a reservoir and dam (profile view) during drawdown sediment flushing, wherein a reservoir is temporarily emptied to induce erosion of previously deposited sediment.

Flushing generally results in the discharge of a large quantity of sediment over a short period of time, out of sync with a river's natural sediment transport patterns. Sediment routing offers an alternative to flushing. Sediment routing is generally performed in one of two ways: sediment bypassing or sediment pass-through. Both bypassing and pass-through are typically performed during high flow conditions (e.g., during the monsoon season), which is often when the majority of the river's annual sediment load is transported. Sediment bypassing, which is not considered here because it requires a relatively steep gradient, routes the sediment-laden water around the reservoir to prevent deposition. Conversely, sediment pass-through, which will be explored in this study, routes the water directly through the reservoir by maintaining a high sediment transport capacity. The most common examples of sediment pass-through include sluicing and density current venting. Sluicing involves increasing sediment transport capacity by reducing water levels to that of the mid-level gates and discharging high flows during the flood season (e.g., First Falls Dam in South Africa). Density current venting involves maintaining normal reservoir water levels but opening low level outlets to release high-concentration sediment plumes (called density currents) that may form at times as sediment flows into a reservoir (e.g., Xiaolangdi Dam in China). In this study, we do not directly simulate sluicing or density current venting. Instead, we investigate a form of sediment routing that is a combination of flushing and sluicing.

To simulate sediment routing, the reservoir is emptied near the beginning of the wet season to permit initial flushing of the reservoir, after which the reservoir is kept empty throughout the majority of the wet season to allow inflowing floods to transport their sediment through the reservoir without deposition. (It is beneficial to empty the reservoir before the peak of the wet season, to ease the process of emptying the reservoir). As depicted in Figure 3.3, maintaining free flow conditions throughout the wet season will require large, low-level radial gates that effectively render the dam "transparent" during the flood season. This technique is potentially environmentally beneficial because it permits much of the annual sediment load to be discharged naturally, in both timing and concentration, assuming upstream dams have not completely disrupted such natural patterns. As sediment deposition is significantly minimized in this approach, a secondary benefit of it is that sediment loads available to be released during the initial opening of radial gates (flushing) are significantly reduced. Third, compared to flushing, such significant discharge from the reservoir is likely to increase discharge of coarse sediment and bedload, which flushing has difficulty releasing, often resulting in a coarse delta that progrades into the reservoir [*Morris and Fan*, 1998]. A similar combination of techniques is practiced at Sanmenxia Dam in China [*Wang et al.*, 2005] and at Jensanpei reservoir in Taiwan

[*Huang*, 1994]. The pass-through portion of this technique is very similar to sluicing, but is not identical to sluicing as many authors define it, as sluicing involves only partial drawdown of the reservoir, after which discharge is controlled with the use of mid-level gates. Thus, sluicing may allow for energy producing during the wet season, depending upon the concentration and hardness of sediment being sluiced.

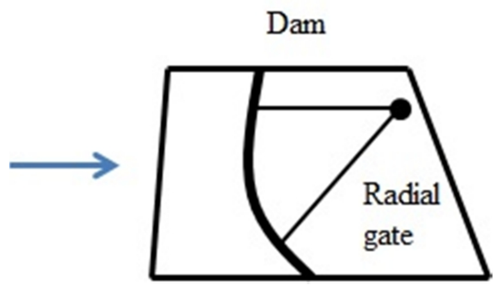


Figure 3.3: Cross-sectional sketch of a dam with large radial gates installed in the dam along its length. The arrow indicates the direction of flow from upstream to downstream. The radial gates are opened during drawdown flushing, routing or sluicing to effectively render the dam "transparent", as the gates enable river-like flow conditions through the dam during drawdown. Note that smaller, low-level outlets can be effective for short-duration flushing.

3 Methodology

3.1 Modeling Tools and Data

A schematic describing the modeling tools used in this study is given in Figure 3.4. The unregulated hydrology in the 3S basins is simulated with a calibrated Soil and Water Assessment Tool (SWAT) model maintained by the MRC [*MRC*, 2011a], which was calibrated and validated using data from 1985-2008. To simulate sediment production, sedimentation, and specific sediment management practices, we developed a one-dimensional, deterministic daily time step simulation tool, *SedSim*, to predict in relative terms the spatial and temporal accumulation and depletion of sediment in river channels and in reservoirs under different reservoir operating and sediment management policies [*Wild and Loucks*, 2012]. *SedSim* simulates flow, sediment and hydropower production, given various multiple reservoir sediment management techniques (e.g., sediment flushing, sluicing, bypassing, density current venting, and dredging). The REServoir CONServation (RESCON) Model [*Palmieri et al.*, 2003] is a pre-feasibility sediment management tool used to verify the technical and economic feasibility of specific sediment management techniques evaluated at the reservoir sites considered here, such as sediment flushing [*Annandale*, 2012], before they are evaluated using *SedSim*.

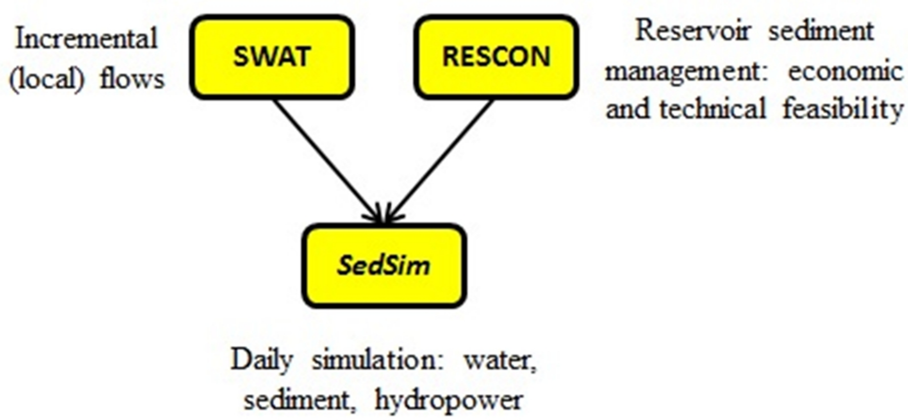


Figure 3.4: A schematic demonstrating the modeling tools used to conduct this study, including the Soil and Water Assessment Tool (SWAT) for incremental (local) flows; the *SedSim* model for sediment production, trapping and sediment management; and the REServoir CONServation (RESCON) model for assessing the technical and economic feasibility of specific sediment management techniques (e.g., flushing).

Methods used to generate sediment loads from sub watersheds and trap sediment in reservoirs are detailed in *Wild and Loucks* [2014a]. To briefly summarize, reliable and extensive sediment data are not publicly available in the 3S basins. Recent flow and sediment sampling efforts at the confluence of the 3S basins and the Mekong River, as well as within the 3S basins, should permit calibrating a SWAT model to generate daily sediment loads from SWAT sub watersheds. However, until this becomes available, this study makes use of the best available sediment data produced by *Kondolf et al.* [2011], which predicts sediment yield in different parts of the 3S basins based on climatic, geologic, topographic and tectonic features. Given the assumption that the 3S basins system is in relative balance in its unregulated state, exporting approximately what is eroded on an average annual basis [*Kondolf et al.*, 2011; *Kondolf et al.*, 2014; *Ta et al.*, 2002], the result of this approach is that about 22.7 Mt/yr of sediment is generated in the unregulated 3S basins. This is consistent with the suggestion by *Sarkkula et al.* [2010] that annual sediment production in the range of 10-25 Mt/yr for the 3S basin is reasonable. Of this 22.7 Mt/yr, about 14.2 Mt/yr on average are discharged past the proposed LSS2 dam site.

Annual sediment load predictions in various sub watersheds i were partitioned into daily sediment loads by employing a rating curve [*Milliman and Meade*, 1983; *Morehead et al.*, 2003] based on the power regression of suspended sediment concentration, C_s (kg/m^3), on daily local discharge, Q (m^3/s), as given by Eq. (3.1)

$$C_s = a_i Q_i(t)^{b_i} \tag{3.1}$$

Values for parameters a_i are calibrated for each incremental input location (e.g., reservoir site) based on assumptions about values for parameter b_i (discussed in more detail later), with the goal of generating the mean annual sediment load inflow for each reservoir site based on specific sediment yields provided by *Kondolf et al.* [2011].

The fraction of inflowing sediment mass trapped in each day in 3S basins reservoirs, or trapping efficiency, is determined using the empirical Brune curve approach [*Brune*, 1953], and is a function of sediment size and residence time of water in the reservoir. Bulk density of sediment is assumed to be 1200 kg/m3, based on the reported density of sediment in the Vietnam Delta [*Xue et al.*, 2010]. Simulations were conducted for 100 years because this is a typical assumption regarding the lifetime of a dam, allows adequate time for sedimentation to impact storage capacity, captures the declining rate of trapping efficiency reservoirs may experience over time, and captures important long-term process such as the evolving shape of the incised channel formed in the reservoir during sediment flushing and routing.

3.2 Overview of the Lower Se San 2 (LSS2) Dam Alternatives

The proposed LSS2 Dam (see location in Figure 3.1) was not designed with sediment management goals in mind. The reservoir is not only large, which will create significant sediment trapping due to increased residence time, but is also too wide and flat (the 7.7 km long dam would create a 33,560 hectare reservoir) for common sediment management practices to be feasible. *Annandale* [2012] has proposed alternative configurations for these dams to reduce sediment trapping and enable sediment management (see Table 3.1 and Figure 3.5). Specifically, *Annandale* [2012] proposed (1) relocating the dams to nearby but narrower spots on the river that will permit sediment flushing; (2) building low-level outlets into the dam to permit sediment flushing; and (3) reducing reservoir size (volume and length) to reduce sediment trapping and make sediment flushing feasible, given that the reservoir must be completely emptied to conduct flushing. Given that flushing and routing are feasible at the alternative dams, here we develop and evaluate alternative operating policies that should enable these sediment management practices to occur.

Table 3.1: Information about the currently proposed Lower Se San 2 (LSS2) Dam, as well as three dams that, together, could serve as an alternative option to replace LSS2 to reduce sediment trapping: Lower Se San 2-II (LSS2-II), Lower Sre Pok 2 (LSP2), and Se San Upstream 1 (US1). Dam and reservoir specifications related to the three alternatives are borrowed and adapted from *Annandale* [2012].

	LSS2[a]	LSS2-II[b]	LSP2[c]	US1[d]
Total Reservoir Storage Capacity (10^6 m^3)	1,793	136.9	258.6	231.5
Dam Length (km)	7.7	1.2	1.2	2
Reservoir Length (km)	50	16	21	20
Installed Capacity (MW)	480	122	138	76
Rated Head (m)	26	14	14	10
Design discharge (m^3/s)	2119	996	1123	864
Operating Policy	Run-of-river	Run-of-river	Run-of-river	Run-of-river
Low Level Flushing Outlets?	No	Yes	Yes	Yes
Mean Annual Unregulated Inflow Rate (m^3/s)	1544	731	813	630
Mean annual unregulated sediment inflow (Mt/yr)[e]	14.3	5.4	8.9	4.7
Mean annual regulated sediment inflow range (Mt/yr)[e]	2.4-7.7	1-2.6	1.4-7.2	0.3-2.3

[a] LSS2: Lower Se San 2 Dam as currently planned.
[b] LSS2-II: Lower Se San 2-II Dam, one of three dams proposed here to replace the currently planned Lower Se San 2 Dam.
[c] LSP2: Lower Sre Pok 2 Dam, one of three dams proposed here to replace the currently planned Lower Se San 2 Dam.
[d] US1: Se San Upstream 1 (US1) Dam, one of three dams proposed here to replace the currently planned Lower Se San 2 Dam.
[e] The unregulated mean annual sediment load inflows (Mt/yr) to the dam sites are provided by *Kondolf et al.* [2011, 2014]. Regulated mean annual sediment load inflows (Mt/yr) are simulated with *SedSim*, the range representing the inflows possible in the high and low sediment inflow scenarios.

To reflect these concepts, the alternative to LSS2 considered here (see Figure 3.5) is to replace the currently proposed LSS2 Dam with three smaller dams: Lower Sre Pok 2 (LSP2) on the Sre Pok River, and Lower Se San 2-II (LSS2-II) and Se San Upstream 1 (Se San US1) on the Se San River. Both sediment flushing and a form of sediment routing would be possible at all three alternative dams due to their reduced size, availability of low level outlets, and locations. The alternatives simulated here are similar to those proposed by *Annandale* [2012], with some modifications to reflect improved hydrologic data. Note that in simulating sediment inflows to the LSS2 site, we assume no sediment management practices take place upstream of the LSS2

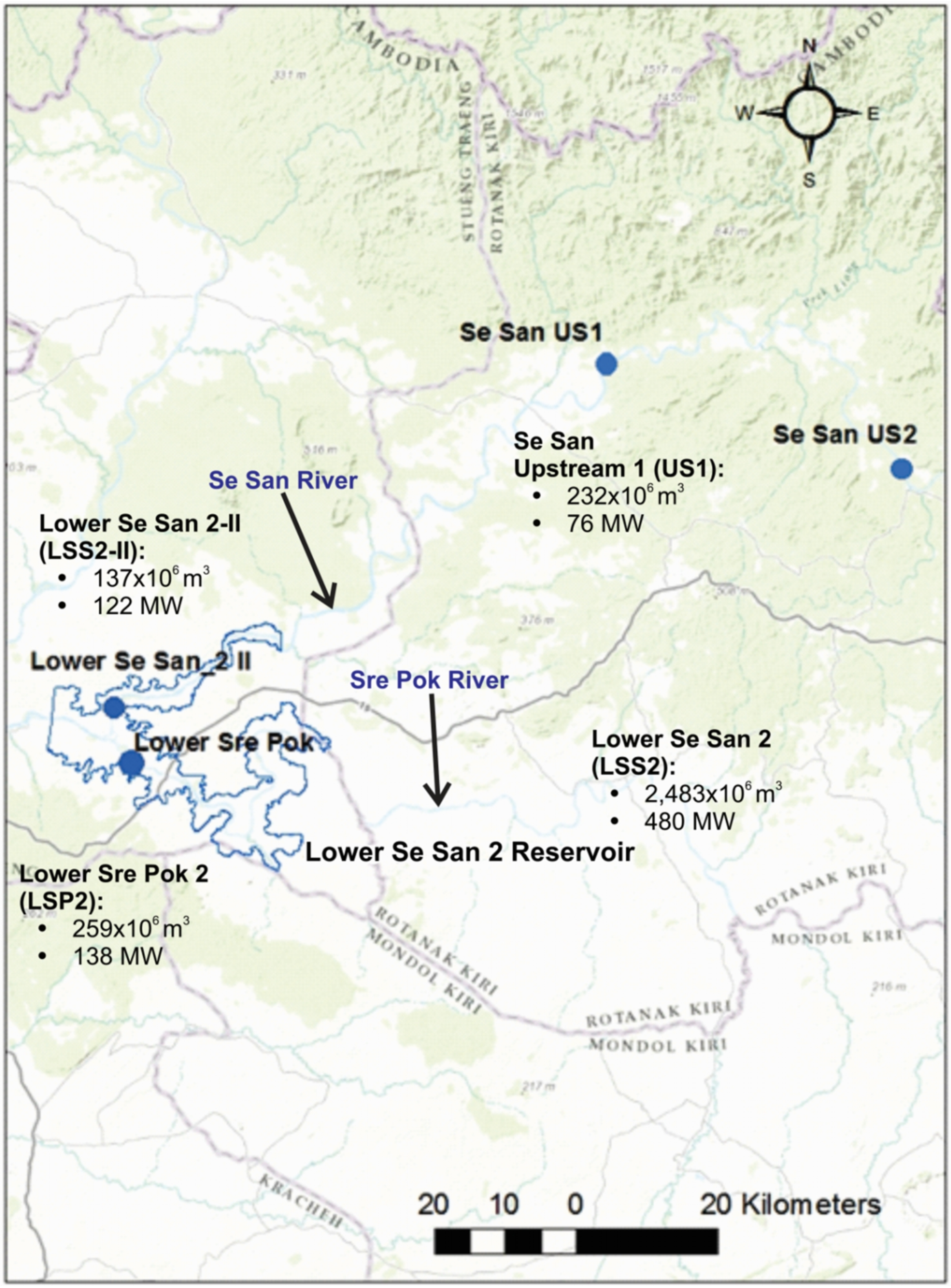


Figure 3.5: Map of the currently proposed Lower Se San 2 (LSS2) Dam, which spans across the Se San and Sre Pok Rivers, and three smaller alternative dams that could be considered to replace LSS2 for sediment management purposes: Lower Se San 2-II (LSS2-II), Lower Sre Pok 2 (LSP2), and Se San Upstream 1 (US1). The LSS2-II and LSP2 reservoirs would be sited within the bounds of LSS2 reservoir as currently planned. Storage capacities (m3) and hydropower plant installed capacities (MW) are shown. The figure (and dam specifications listed on map) are borrowed and adapted from *Annandale* [2012][3].

[3] Figure is adapted from Annandale, G.W. (2012), *A Climate Resilient Mekong: Sediment Pass Through at Lower Se*

dam site. Table 3.1 provides information about the proposed LSS2 Dam [MRC, 2012; CNMC, 2009] and alternatives [Annandale, 2012], while Table 3.2 provides specific information regarding flushing and routing assumptions, and scenarios simulated for the alternative dams, respectively.

3.3 Flushing in SedSim: Assumptions Regarding Reservoir Operations

3.3.1 Summary of Flushing Procedure

The *SedSim* flushing procedure consists of three components: drawdown, flushing, and refill, for which associated assumptions are listed in Table 3.2. Simulated examples of both successful and unsuccessful flushing procedures are shown in Figure 3.6. On or after the specified date on which drawdown may first be considered, *SedSim* initiates the drawdown process on the first day on which the daily reservoir inflow exceeds the specified minimum required inflow. This process prevents a drawdown that begins on the same pre-specified date every year, which can result in drawdown too early in the dry season, before flows at the beginning of the wet season begin to increase. Figure 3.6a illustrates two examples of simulated reservoir inflow rates (m^3/s) in the DF scenario that trigger drawdown to attempt flushing (to achieve flushing equal to the mean annual inflow (MAF)), but do not ultimately result in successful flushing. In Case 1 (1990 flows), inflow rates quickly rise and exceed the release capacity of the dam's outlets, remaining this way for the remainder of the year, thus preventing flushing. In case 2 (1985 flows), drawdown is triggered, but upon drawdown, inflow rates are only 50% of the target flow, thus greatly limiting flushing success. In Figure 3.6b, simulated results for a third inflow case are shown wherein flushing is successful. Results include inflow

---

San 2, Golder Assoc. Inc., Lakewood, CO, Nat. Heritage Inst., San Francisco, CA.

and outflow rates and reservoir storage (m^3), including demarcation of the drawdown, flushing and refill components of the process.

Table 3.2: Important assumptions employed regarding the sediment flushing and drawdown routing processes at the three alternative dams: Lower Se San 2-II (LSS2-II), Lower Sre Pok 2 (LSP2), and Se San Upstream 1 (US1). Flushing was not attempted at Lower Se San 2 (LSS2) dam as planned because the reservoir is too large for sediment management to be feasible.

	LSS2-II[a]		**LSP2**[b]		**US1**[c]	
	Flushing	*Routing*	*Flushing*	*Routing*	*Flushing*	*Routing*
Target Average Start Month[d]	June-August	July 1st	June-August	July 1st	June-August	July 1st
Inflow Rate Triggering Drawdown (m^3/s)[d]	500-850	--	550-1000	--	450-700	--
Maximum Drawdown Rate (m/day)	2	2	2	2	1.5	1.5
Target Duration (days)	3	90	3	90	3	90
Target Flushing Discharge (m^3/s)[e]	730, 1100	--	815, 1220	--	630, 945	--
Simulated Frequency	Annual, Biannual	Annual, Biannual	Annual, Biannual	Annual, Biannual	Annual, Biannual	Annual, Biannual

[a] LSS2-II: Lower Se San 2-II Dam, one of three dams proposed here to replace the currently planned Lower Se San 2 Dam.
[b] LSP2: Lower Sre Pok 2 Dam, one of three dams proposed here to replace the currently planned Lower Se San 2 Dam.
[c] US1: Se San Upstream 1 (US1) Dam, one of three dams proposed here to replace the currently planned Lower Se San 2 Dam.
[d] Ranges are provided because both the target drawdown date and the reservoir inflow rate (m^3/s) triggering drawdown for flushing depend on the inflow regime, which depends on the extent of upstream development (DF or FD scenario) and nature upstream reservoirs' operating policies (FSL or SV).
[e] Two target flushing discharge rates are provided, as flushing discharge targets equal to both the mean annual inflow and 1.5 times the mean annual inflow are simulated.

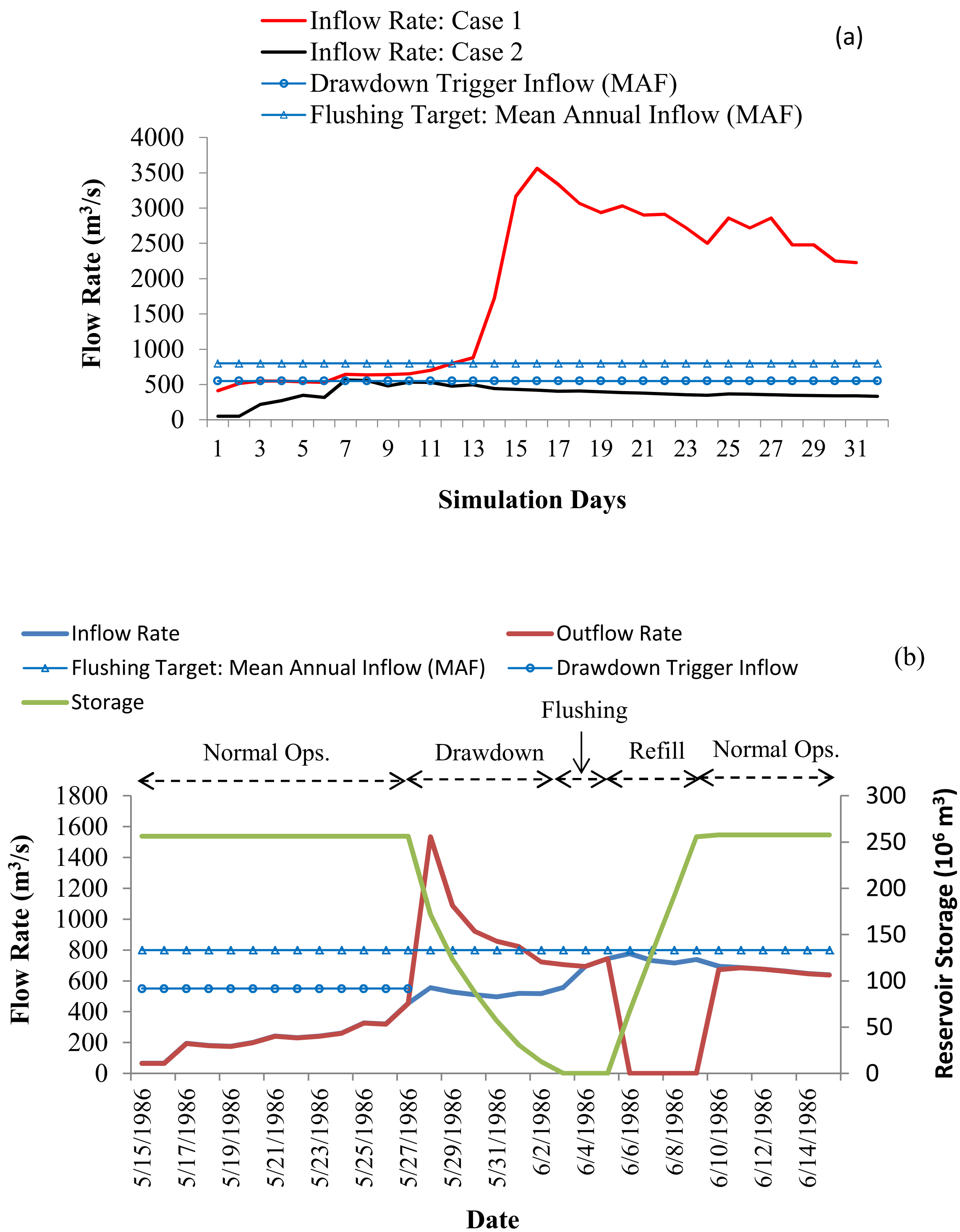


Figure 3.6: Demonstration of the flushing process as simulated in *SedSim* for the alternative reservoir Lower Sre Pok 2, for (a) two hydrologic inflow years that prevented flushing (Case 1) or reduced flushing effectiveness (Case 2), and for (b) a successful flushing case, including reservoir inflow and outflow rates (m^3/s) and reservoir water storage (m^3).

Once drawdown is triggered, the hydropower and low level outlets are used to drain the reservoir to the elevation of the low level outlet (i.e., the original river bed elevation), but the rate of drawdown must not exceed the specified maximum drawdown rate (2 m/day in this case). This 2 m/day rate reduces the possibility of inducing bank failure or landslides within the reservoir, ensures peak flows released downstream during drawdown are reasonable in comparison to typical wet season discharges, and limits drawdown duration to about one week, on average.

Once the reservoir is drained, flushing proceeds for three full days at each dam before flushing is completed and refill can begin. This flushing duration was determined based upon a review of typical flushing operations at various dams [*Atkinson*, 1996; *Morris and Fan*, 1998]. Two conditions must be satisfied for three full days before flushing is considered complete and refill is initiated: (1) the water surface elevation (masl) is maintained at the low level outlets (i.e., free flow is achieved), and (2) the discharge through the low level outlets exceeds the minimum flushing inflow requirement (m^3/s). (For this reason, drawdown can last longer than 3 days). Free flow conditions are required to ensure that high enough scouring velocities exist to generate significant erosion. Due to the significant uncertainty in estimating flushing discharge requirements, flow constraints are assumed to be satisfied if flushing discharge is within 30% of the target discharge. The reservoir will only remain drawn down seeking to satisfy the inflow and elevation conditions for one week. Once the flushing process is complete or the maximum drawdown time has been exceeded, refill begins in the next time period. No minimum energy generation requirement during refill is specified in this study, given that the minimum, maximum and rated heads of the alternative dams' turbines are not known.

3.3.2 Timing of Flushing

Selection of the date on which to permit reservoir drawdown (if the minimum inflow requirement is exceeded) required some experimentation for each alternative. Flushing dates shown in Table 3.2 avoid the drawbacks of conducting flushing during the main portion of either the wet or dry season. Performing flushing during the wet season is very difficult because inflows are high, so reasonably sized low-level outlets will not have sufficient capacity to quickly and safely empty the reservoir, and maintain free-flow discharge (i.e., without ponding) during flushing. This results in highly uncertain flushing success and associated energy losses. Outlets could be over-sized to accommodate large inflows, but doing so can be costly. (In this study, large radial gates are assumed to exist for simulations of sediment routing to permit passage of large inflows, but drawdown is conducted prior to the peak of the wet season).

Conversely, performing flushing during the main portion of the dry season is problematic for three reasons. First, natural reservoir inflows are lower, which greatly reduces the effectiveness of flushing because the cross-sectional area of the incised channel formed by flushing is smaller. It could be possible to manage this difficulty by supplementing local reservoir inflows (at LSS2-II, US1, and LSP2) with strategic releases from two planned upstream Cambodian reservoirs: Lower Sre Pok 4 (LSP4) and Lower Se San 3 (LSS3). However, even though all five reservoirs would be operated within Cambodia, it is not clear that the entire suite of reservoirs would be operated by a single entity. For this reason, a successful, cooperative sediment management policy involving the entire suite of five reservoirs is not necessarily realistic. Second, significant energy losses relative to typical production are possible if flushing is performed in the dry season. Reservoirs would be taken offline during a time of year when temperatures are high, and hydropower energy is highly valuable given the lower availability of natural reservoir inflows during this time. Also, refill of the reservoir may be time consuming and more uncertain during the dry season, thereby impacting energy production targets and firm power. Third, flushing during the dry season introduces large sediment loads into the local environment downstream of the flushed dams during a time of year when large magnitude sediment events are unexpected by local aquatic ecosystems that have adapted to natural conditions, and naturally high flows are not available to rinse the downstream channel of accumulated sediments.

Given the above reasoning, flushing at the considered set of reservoirs is best conducted during the period of time when the reservoir is transitioning from the dry season into the wet season (May-July, depending on the year), as shown in Figure 3.7. Target flushing flows were accordingly established to reflect the inflows to each reservoir during this transition season. In this case, a target flushing discharge of 1.0 to 1.5 times the mean annual inflow would, on average, produce flushing during this desired time period. During this time of year, inflows are large enough to remove significant quantities of sediment without being too large to render drawdown difficult or require very large low-level outlets to prevent ponding during flushing. Next, inflows are typically large enough to produce reasonable reservoir refill times. Additionally, the hydrologic system naturally produces short duration storm events that produce natural spikes of flow and sediment during this time of year. These spikes serve as a natural indicator to ecosystems that the river basin is transitioning from the dry season to the wet season, triggering events such as fish migration for certain species. Because these spikes in sediment discharge occur naturally, flushing during this transitional period may be more favorable than doing so during the dry season, if sediment concentration and loading can be controlled [*MRC*, 2009b; *Baran and Nasielski*, 2011]. Unfortunately, from a reservoir operations perspective, flushing during this time frame significantly increases the likelihood of drawing down a reservoir due to high inflows associated with a particular storm event, but experiencing inadequate inflows (below the target flushing discharge) on the receding limb of the storm event's hydrograph once the reservoir is finally empty (see Figure 3.6a).

3.3.3 Coordinated Multiple Reservoir Operations

Coordinated operations between the three alternative dams and the primary large upstream reservoirs (LSS3 and LSP4) is not demonstrated in the results, both because it may be impractical and because results (to be discussed) suggest that such coordination is not necessary. However, flushing dates listed in Table 3.2 do reflect loosely coordinated operations in two cases: (1) between LSS2-II and US1, and (2) between LSS2-II and LSP2. It is reasonable to assume such coordination given the proposal that the three alternative dams be constructed by the current developer in place of LSS2. Regarding LSS2-II and US1, due to their proximity, the two dams are often hydrologically triggered to draw down for flushing at approximately the same time. When flushing does occur in the dams at similar times, in order to maximize sediment passage through the two dams, LSS2-II is not refilled until US1 completes its flushing. Note that this approach is expected to very slightly reduce energy production because LSS2-II remains empty for longer than it otherwise would to accommodate the flushing discharge from US1. Coordination between the two reservoirs would be important in practice given the likely lack of real-time forecasting and the proximity of LSS2-II and US1.

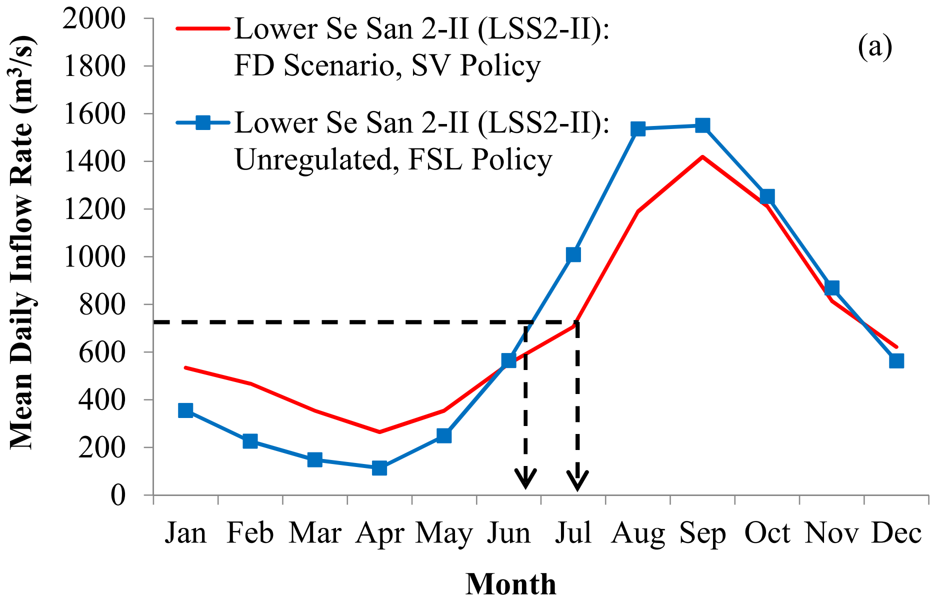


Figure 3.7: Mean daily inflow rates (m^3/s) in each month to alternative reservoirs (a) Lower Se San 2-II and (b) Lower Sre Pok 2, for various combinations of basin development (unregulated, Definite Future (DF) and Full Development (FD) scenarios) and system-wide operating policies (Full Supply Level (FSL) run-of river, and seasonal variation (SV)). The Full Supply Level (FSL) policy result in inflows nearly identical to the unregulated inflows to each site, and only appears once because it is nearly identical in both development scenarios. The figure also demonstrates the average timing of successful reservoir flushing at each site. Note that mean daily while monthly mean reservoir inflows are shown, these values are very similar to monthly mean outflows, given the assumption of run-of-river operations at the alternative dam sites.

For example, if three uncoordinated entities operated the three alternative dams, the US1 operator could observe high inflows and empty the reservoir to conduct flushing. The LSS2-II operator could observe high inflows (due to the emptying of US1) and draw down LSS2-II to prepare for flushing, but receive no inflows upon drawdown because US1 has completed flushing and is being refilled. We assume some degree of coordination, and thus prevent such occurrences. Furthermore, coordination permits sediments flushed from US1 to pass through LSS2-II, without a large fraction of the sediment setting in LSS2-II such that it cannot be accessed by the incised flushing channel.

The second operational assumption that reflects coordinated behavior is that flushing at the LSS2-II and US1 sites is conducted at slightly different times than flushing at the LSP2 site. This optimal coordinated timing difference, which often occurs naturally given the slight hydrologic differences between the Sre Pok and Se San Rivers, allows clear water released from either LSS2-II or LSP2 to dilute the sediment concentration being released from the other dam during its respective flushing procedure, and provide additional transport capacity to prevent large quantities of sediment from settling on the river bed downstream of the confluence of the two rivers. Also, note that separating LSS2 dam into two smaller dams (LSS2-II and LSP2) creates the opportunity to perform flushing in alternating reservoirs in alternating years (i.e., bi-annual alternating flushing as listed in Table 3.2 and Table 3.3) to possibly reduce the impact of sediment releases on downstream ecosystems while improving the reliability of hydropower production in comparison to annual and regular biannual flushing schedules.

3.3.4 Frequency of Sediment Management

The appropriate recurrence interval for flushing depends on the conditions at the reservoir site. Both annual (every year) and bi-annual (every other year) flushing options for the alternative reservoirs are evaluated here. Regularly performed flushing is advantageous for two reasons. First, sediment that remains deposited in a reservoir for more than a few years can become consolidated, which makes erosion of sediment deposits more difficult. Second, the longer the duration in between flushing events, the more sediment is discharged during each flushing event, which is an environmental concern for the reasons previously described. However, more frequent flushing results in more frequent hydropower losses. It will not be possible to explore every combination of sediment management techniques and frequency of implementation at the alternative dams. Instead, a subset of all possible scenarios were simulated, as shown in Table 3.3.

Table 3.3: Summary of sediment management scenarios considered at Lower Se San 2 (LSS2), and three alternative dams that could replace LSS2 to improve sediment passage: Lower Se San 2-II (LSS2-II), Lower Sre Pok 2 (LSP2), and Se San Upstream 1 (US1).

	Reservoirs			**Flushing**			**Routing**		
			LSS2-II[a]	Frequency			Frequency		
			LSP2[b]		Biannual			Biannual	
Scenario	No dams	LSS2	US1[c]	Annual	Regular	Alternating	Annual	Regular	Alternating
1	x								
2		x							--
3			x						
4			x	x					
5			x		x				
6			x			x			
7			x				x		
8			x					x	
9			x						x

[a] LSS2-II: Lower Se San 2-II Dam, one of three dams proposed here to replace the currently planned Lower Se San 2 (LSS2) Dam.
[b] LSP2: Lower Sre Pok 2 Dam, one of three dams proposed here to replace the currently planned LSS2.

[c] US1: Se San Upstream 1 (US1) Dam, one of three dams proposed here to replace the currently planned LSS2.

3.4 Sensitivity Analysis

The objective of sensitivity analysis in this study is to evaluate the sensitivity of the effectiveness of sediment flushing and routing techniques, as well as associated energy production tradeoffs, to various assumptions. Most assumptions are taken to be known with certainty (e.g. reservoir storage capacities and outlet release capacities). A smaller subset of factors and assumptions impacting results are taken here to be less certain and are thus subject to sensitivity analyses, including extent of basin development, reservoir operating policies, sediment size, sediment rating curve relationships, and sediment released during flushing (which depends on target flushing discharge, sediment density, and reservoir dimensions).

To reduce the number of potential sediment management scenarios to consider from several hundred (involving various combinations the above factors with various sediment management scenarios) to a more manageable number, sensitivity analysis conducted by *Wild and Loucks* [2014a] indicated that two primary factors influence sediment load inflow to the LSS2 site: extent of basin development, and sediment size. To capture a reasonable range of possible sediment inflows to the site, two sediment inflow scenarios are simulated that capture the upper and lower inflows to the site:

1) High inflow scenario, which includes the highest number of dams (FD scenario) and coarsest sediment size (upper Brune curve), both of which are defined below; and
2) Low sediment inflow scenario, which includes fewer dams (DF scenario) and finer sediment size (the lower Brune curve).

Assumptions regarding upstream basin development and sediment size are as follows:

1) **Extent of basin dam development (i.e., number and location of reservoirs in the 3S basins).** Three scenarios are considered:
   a. *Unregulated Scenario*. No dams.
   b. *Definite Future (DF) Scenario*. This scenario includes 25 dams (13 in Vietnam, 1 in Cambodia, and 11 in Lao PDR) that are either existing, under construction, or expected to be constructed in the near future (next five years, or by 2018), at a total installed capacity of 4.5 Gigawatts (GW). Lower Se San 2 is included in this scenario, but five Cambodian dams on the Sre Pok and Se San Rivers are excluded: Lower Se San 3, Lower Sre Pok 3, Lower Sre Pok 4, Prek Liang 1, and Prek Liang 2.
   c. *Full Development (FD) Scenario*. This scenario includes all 41 existing, under construction and planned dams (13 in Vietnam, 6 in Cambodia, and 22 in Lao PDR), at a total installed capacity of 6.6 Gigawatts (GW).
2) **Sediment size selection.** Two curves proposed by *Brune* [1953] are simulated to reflect that different fractions of inflowing sediment are trapped depending on the size and type of sediment being deposited:
   a. Lower trapping curve for colloidal, dispersed and fine-grained particles
   b. Upper trapping curve for flocculated and coarse sediments.

The remaining factors are considered to be more important to the effectiveness of sediment management, as well as to the magnitude, frequency and timing of sediment released during sediment management, and are thus subject to sensitivity analyses:

1. **Reservoir operating policies.** Planned operating policies in this rapidly changing basin are difficult to acquire, and in some cases are still unknown. *Wild and Loucks* [2014a] proposed three system policies, similar to those proposed by *Piman et al.* [2013], to provide reasonable bounds on the range of possible future outcomes that could result from different combinations of operating policies throughout the 3S basins. Changing these system operating policies did not significantly change mean annual trapped sediment loads in 3S basins reservoirs [*Wild and Loucks*, 2014a]. However, two operating policies have different effects on the Sre Pok and Se San Rivers' flow regime, which affects the optimal timing and success of sediment flushing and routing operations. The two policies considered are:
   iv) *Full supply level policy (FSL)*. This is a run-of-river policy with the goal of maintaining the water surface elevation at the upper level (or full supply level) of the active storage zone.
   v) *Seasonal variation (SV) policy*. This policy attempts to reduce spilling by filling the reservoir during the wet season and emptying the reservoir during the dry season.
2. **Sediment Released During Flushing Events.** The quantity of sediment removed during a particular flushing event is some fraction of the sediment that has settled since the most recent past flushing event. This fraction is a function of the average cross-sectional dimensions of the incised channel formed by flushing relative to the reservoir's average cross-sectional dimensions [*Atkinson*, 1996], which changes during simulation as the flushing channel grows over time. The reservoir's cross-sectional dimensions are fixed, so the sensitivity of this ratio to variability in flushing channel dimensions is evaluated, which depends on flushing target discharge (m^3/s), for which two options are considered:
   i. Mean annual inflow rate (m^3/s)

ii. 1.5 times the mean annual inflow rate (m^3/s)

These two flushing discharge targets, combined with the relative cross-sectional dimensions of the flushing channel and reservoir, will produce flushed sediment loads that constitute the lower/expected results in the envelope of potential flushing success. To provide an upper/maximum limit on the success of flushing, results are also generated for scenarios in which flushing in each year is capable of removing all sediment that has settled since the previous flushing event.

3. **Parameters "a" and "b" in Eq. (3.1), used to generate incremental sediment loads in the local sub-watersheds (between reservoir sites).** A value for "b" in Eq. (3.1) must be assumed so that an "a" value can be calibrated. Thus, the selection of "b" affects the value of "a". For sensitivity analysis, "b" values were varied in the range from 0.2 to 1.6, and corresponding "a" values were calibrated. This is a reasonable range given the rating curve relationships established for the Mekong River [*Walling*, 2008; *Wang et al.*, 2011] and on the 3S tributaries using very limited gage data [*PECC1*, 2013]. *Wild and Loucks* [2014a] showed that varying these parameter values did not significantly change mean annual trapped sediment loads in 3S basins reservoirs. Instead, these parameters mostly affect how sediment load is distributed between flow events in the wet and dry seasons. For example, increasing the "b" value (e.g., from 1.0 to 1.5) distributes more of the sediment load generation into high flow events in the wet season. This is important because it affects the relative severity of the magnitude of sediment discharged during sediment management events, which is an important consideration for downstream aquatic ecosystems.

4 Results and Discussion

4.1 Sediment Management: Impact of Hydrologic Inflows on Sediment Management

The flow regime at the alternative dam sites will play a large role in the ultimate success of flushing. As shown in Figure 3.7, inflows to the alternative dam sites depend on both the extent of upstream development and the operating policies of those upstream dams. The scenarios presented here are designed to conduct flushing during a time when inflows are on average equal to (1) the mean annual inflow and (2) 1.5 times the mean annual inflow. These flow values are indicated on Figure 3.7 to suggest the time periods during which flushing would be expected to occur. In Figure 3.7, only two of four possible inflow scenarios are shown for LSS2-II and LSP2. This is because (1) the FSL run-of-river operating policy is nearly identical in both development scenarios, and (2) in the DF scenario, upstream operating policies do not significantly influence inflows to the alternative reservoir sites. The latter occurs because (1) the 18 dams upstream of the LSS2 site that exist in this scenario are sited such that they regulate only 45% of the flow in the upper Sre Pok and upper Se San Rivers, and (2) many of the dams maintain run-of-river operations. In the FD scenario, the addition of four large (and two small) Cambodian reservoirs upstream of the LSS2 site creates significant flow regime alteration, assuming the SV system operating policy. The SV policy in the FD scenario slightly delays the optimal hydrologic timing of flushing by 2-4 more weeks into the wet season.

It is notable that simulations demonstrate that adequate inflows exist to conduct flushing at the alternative dam sites for the full range of assumed dam development and reservoir operations upstream. This is interesting for two reasons. First, we propose that flushing could be conducted during the May-July time frame, when monsoon-driven storms tend to create sporadic behavior in inflows as the hydrograph rises. Flushing was successful with high frequency despite this variability in hydrologic inflows. Second, in the FD scenario, the inflow regime at the site in the presence of the four large upstream Cambodian reservoirs was adequate to conduct successful flushing operations at the alternative dams without any coordination required with upstream dams.

The absence of any need for coordinated upstream releases is important for two reasons. First, coordination with upstream reservoirs, which could be owned and operated by different entities with different objectives, will be very difficult to successfully implement in practice. Second, particularly for large upstream reservoirs, the proposed timing of flushing occurs immediately after the end of a long dry season, when these relatively large reservoirs have empty active storage capacities, and operators will want to begin storing water as it begins to increase in the wet season. This reduces the attractiveness of making large releases to improve reliability of flushing operations downstream, and is compounded by reduced discharge capacity associated with reduced dry season head, and the likely lack of high-capacity low-level outlet works at these large dams.

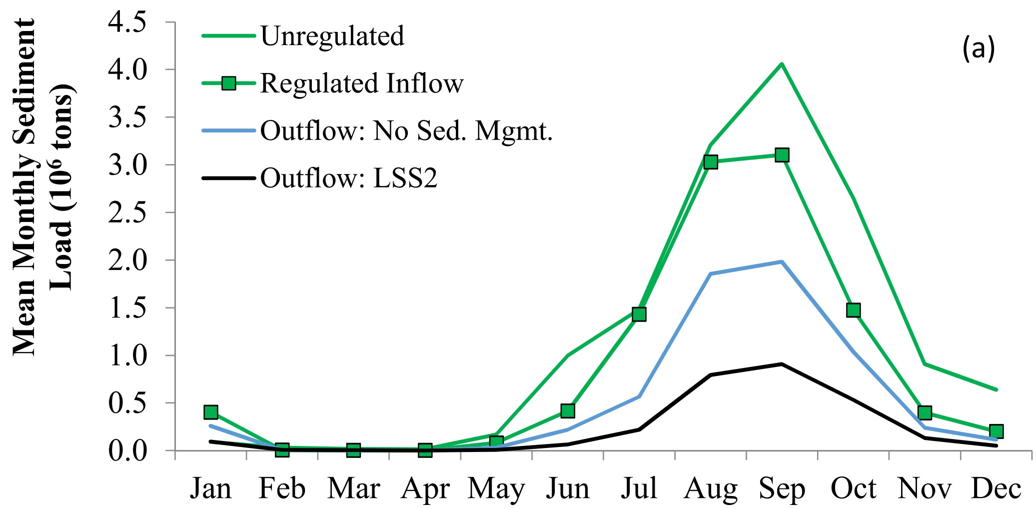
There are two caveats to these observations. First, more information regarding the exact operating policies and specifications of the planned upstream dams is required to verify this result, as this study does not account for peaking, or other sub-daily operations, which could affect the reliability of inflows available for flushing. Second, while successful flushing is possible without releases from upstream dams, coordination could still provide a substantial benefit, as it could reduce the variability in reservoir inflows to the LSS2 alternatives during flushing, which would reduce the variability in environmental impacts downstream. For example, for the annual flushing case with a mean annual inflow target, simulated average flushing discharge was similar to the target discharge, but the standard deviation among different flushing years was 250-300 m^3/s. Third, if the upstream Cambodian dams all ultimately decided to implement sediment management measures similar to those proposed here for LSS2, careful coordination of all 19 dams in Sre Pok and Se San system would be required each year to ensure efficient release of sediment through all dams in the system. This would involve international coordination, as dams on the upper Sre Pok and Se San Rivers are in Vietnam.

Despite the overall success of flushing in the various simulated hydrologic scenarios, Figure 3.6 highlights some additional points regarding the impact of hydrologic inflows on the flushing process. In particular, Figure 3.6a illustrates two hydrologic inflow cases that negatively affect flushing: (1) a high inflow scenario, during which drawdown for flushing is initiated but the reservoir cannot empty due to the magnitude of inflows, and (2) a low inflow scenario, wherein drawdown is initiated, but inflows are only 50% of the target discharge (the mean annual inflow) during the free-flow flushing procedure. During these instances of unsuccessful flushing, much more sediment is released in the following year if successful, similar to conducting biannual flushing. Such circumstances were relatively uncommon, typically occurring only 2-4 times during the 100-year simulation horizon. These instances were more common in scenarios with relatively less regulation of natural flows (e.g., DF scenario, or FSL operating policy with either development scenario), as the unregulated flows tend to demonstrate more variability.

4.2 Sediment Management: Impacts on Sediment Regime

Figure 3.8 demonstrates two important results: (1) the potential impact of LSS2 Dam on the Sre Pok and Se San Rivers' monthly sediment regime, and (2) the potential improvement in sediment discharge that could be achieved by replacing LSS2 with three smaller reservoirs with sediment management practices implemented. These points are illustrated for the high sediment inflow scenario (Figure 3.8a). Note that various combination of "a" and "b" values used to generate incremental sediment loads (see Eq. 1) did not significantly alter the mean monthly sediment loads, nor did the frequency of implementation of sediment management. Rather, the effect of these assumptions on the sediment regime is more visible when discussing peak daily sediment loads, which is discussed later. For example, bi-annual flushing produces nearly identical long-term mean annual sediment loads to annual flushing, though the variance and mean loading peaks associated with less frequent flushing are far less environmentally friendly.

Regardless of the sediment inflow scenario, LSS2 could trap as much as 79% of the inflowing sediment load, and ultimately the sediment discharge from the Sre Pok and Se San Rivers could be significantly reduced at LSS2 (by 1.9 - 7.3 Mt/yr, depending on the sediment inflow scenario). In the low sediment inflow scenario, the magnitude of sediment trapping at LSS2 is less significant due to the significant trapping expected to take place in the 18 dams upstream. Clearly, while run-of-river dams are often considered to be less environmentally harmful due to their relatively small reservoirs and minimal impacts on flow regime, run-of-river dams such as LSS2 can produce a severe alteration of a river's sediment regime. To reduce trapping and increase sediment discharge so it more closely resembles inflow conditions, LSS2 can be replaced with three smaller alternative reservoirs: LSS2-II, LSP2, and US1. The three



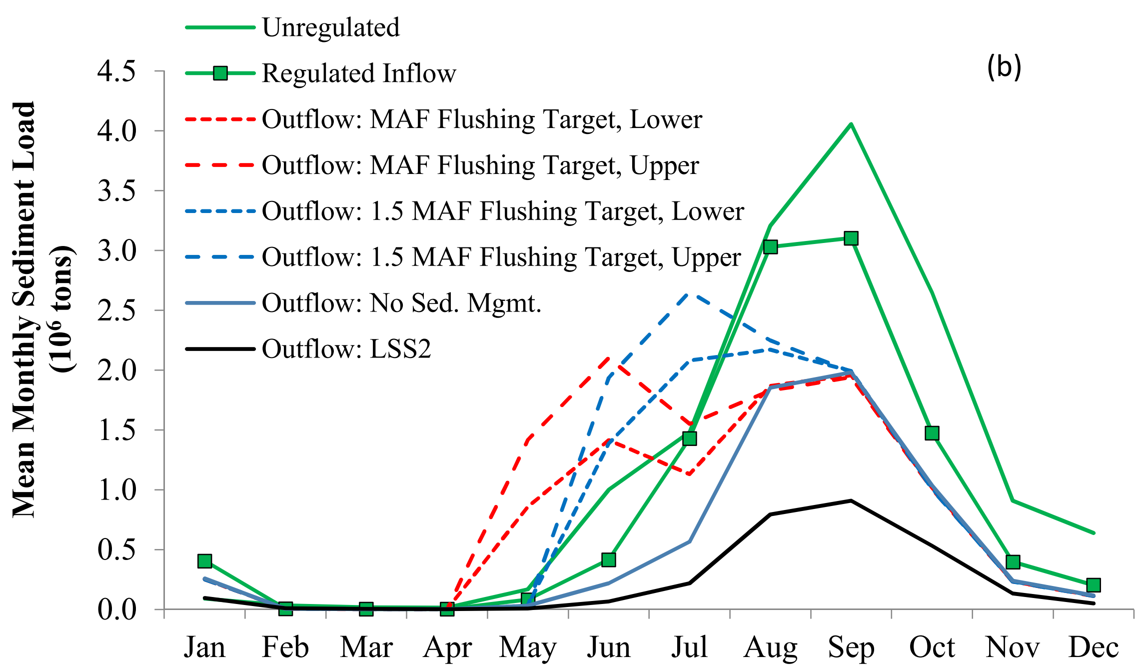


Figure 3.8: Mean monthly sediment load (10^6 tons) inflows and outflows from Lower Se San 2 (LSS2) Dam site, both for the currently planned dam and for the potential set of three alternative replacement dams: Lower Se San 2-II (LSS2-II), Lower Sre Pok 2 (LSP2) and Se San Upstream 1 (US1). This demonstrates the simulated potential for the alternative reservoirs, combined with flushing and routing, to improve sediment passage compared to current plans. Figure 3.8a is intended to demonstrate the effect LSS2, as well as the alternative dams, on the sediment regime when no sediment management plans are in place, whereas Figure 3.8b superimposes various sediment management options onto Figure 3.8a. All outflow time series result from the regulated inflow time series. Results are shown only for the high sediment inflow scenario. Flushing results are shown for two flushing scenarios: one in which the target flushing flow is the mean annual inflow (MAF), and another in which the target flushing flow is 1.5 times the MAF. Upper and lower bounds to flushing success are shown in each case, as defined in section 3.4.

smaller reservoirs have a smaller trapping efficiency, and therefore, depending on a variety of assumptions, could produce a 225- 400% increase in annual sediment discharge compared to LSS2. Sediment management practices have the potential to provide additional improvements.

Figure 3.8 shows that sediment flushing and routing increase sediment discharge from the Sre Pok and Se San Rivers, compared to both LSS2 and the alternatives with no sediment management implemented. In the high sediment inflow scenario, the annual sediment outflow is 8.85-10.5 Mt/yr, depending on assumptions, and outflow is 2.3-2.4 Mt/yr in the low sediment inflow scenario. In the high sediment inflow scenario, flushing produces 140-170% more sediment discharge than the same reservoirs without sediment management, and 315-370% more sediment discharge than LSS2. Annual sediment flushing and routing have the potential to discharge 200-400% more annual sediment load than LSS2 dam. This potentially represents a significant improvement to the integrity of the geomorphologic system in the Sre Pok and Se San Rivers, as well as on the mainstream Mekong River. Given that LMB reservoirs throughout the Mekong basin upstream of the 3S basins could trap 51%-96% of the approximately 137 Mt y^{-1} produced there [*Kummu et al.*, 2010; *ICEM*, 2010; *Kondolf et al.*, 2014], the 2-7.7 Mt y^{-1} of extra sediment released compared to LSS2 as planned could represent a significant percentage of the Mekong basin's total sediment load that remains after basin-wide sediment trapping. In the low sediment inflow scenario, 2 Mt/yr of additional discharge corresponds to 2%-7% (depending on basin-wide trapping efficiency) of the Mekong basin's load, whereas in the high sediment inflow scenario, the 7.7 Mt/yr of additional discharge at LSS2 corresponds to 9%-27% of the Mekong basin's total load.

Figure 3.8 also demonstrates that flushing has the potential to significantly alter the Sre

Pok and Se San Rivers' monthly sediment regime, with peak sediment loads now occurring on average two to three months before the natural mean peak, depending on assumptions regarding hydrologic inflows. However, increases in mean monthly sediment outflows only appear to be significantly higher in the high sediment inflow scenario, with increases in May-July monthly discharge of about 250% compared to unregulated inflows. (Note, however, that mean sediment discharge during May was as much as 5 to 8 times larger than the unregulated loads). This increased load could pose an ecological problem, depending on how well concentrations (and associated durations of release) are controlled, and the sensitivity of plant and animal species downstream of the flushed site to sudden spikes in concentration at this time of year. Design of environmentally friendly flushing policies is discussed in more detail later. Sediment routing clearly offers a more environmentally friendly alternative to flushing, given that associated sediment releases more closely represent natural inflow patterns.

Even if concentrations of sediment releases downstream are controlled, it is unclear whether the discharged sediment would still maintain an ecologically valuable nutrient profile after being stored in the reservoir for an extended period of time, and whether the released sediment and nutrients would benefit the flood-pulse driven ecosystems (particularly in Cambodia). The annual flood pulse, which occurs two to three months after the flushing proposed here, is what encourages the exchange of water, sediment and nutrients between the river and its floodplains, thus driving the system's productivity. Still, Figure 3.8 reveals the alternative reservoirs proposed here are better positioned to release wet season sediment loads than LSS2, due to reduced trapping year round. Additionally, Figure 3.8 demonstrates that annual sediment routing would appear much more likely to reproduce critical wet season sediment loads.

The ultimate extent of upstream development on the Sre Pok and Se San Rivers will influence the success of sediment management at LSS2 and its potential environmental impact. In the DF scenario (which excludes the development of five additional Cambodian dams upstream of LSS2), significant sediment inflows to LSS2 are possible, thereby increasing the effectiveness of sediment management measures at LSS2, but also increasing the magnitude of loads released into the downstream environment. Conversely, if the five Cambodian dams upstream of LSS2 are constructed, setting aside the barriers they would present to fish migration, they will reduce the potential quantity of sediment load that can be trapped in LSS2, thereby reducing the effectiveness of sediment management at LSS2, but also possibly mitigating downstream environmental impacts associated with flushing.

Figure 3.8 also demonstrates some important points regarding the sensitivity of sediment management to various assumptions. In particular, regardless of the sediment inflow scenario and upstream operating policy, the timing of sediment flushing for a flushing target equal to the mean annual inflow is May-July, which is earlier in the year than the June-August time frame for a flushing discharge target of 1.5x the mean annual inflow. Flushing (with a mean annual inflow target) is possible as early as May in scenarios with low flow regulation (DF scenario, or an FSL operating policy) because inflows are not highly regulated (see Figure 3.7). Attempting to achieve a higher target flushing discharge only produces about 10% more sediment than a mean annual inflow target. This occurs because a mean annual inflow discharge already creates an incised channel similar to the dimensions of the river at the location where the alternative dams are sited. However, the 1.5 times higher flushing flows do produce higher mean monthly sediment load peaks, because the flushing events are distributed over a shorter time frame, thereby producing a larger peak. Of the additional factors considered in the sensitivity analysis, there is clearly a difference in the high sediment inflow scenario between the upper and lower limits to flushing success, with the upper limit representing the circumstance in which flushing is capable of removing all sediment that has settled since the previous flushing event.

4.3 Sediment Management: Impacts on Energy Production

Figure 3.9 demonstrates the simulated energy production at LSS2 as planned in comparison to combined mean monthly energy production associated with the three alternative dams and various sediment management practices (i.e., flushing a routing) at those dams. Figure 3.9a shows mean monthly energy production for two different hydrologic inflow regimes: (1) DF scenario and FSL operating policy (essentially unregulated inflows), and (2) FD scenario and SV operating policy (heavily regulated inflows). This demonstrates that variation in the future hydrologic inflow regime will mostly affect the timing (rather than the magnitude) of sediment management-based energy losses. (Note that timing of losses also differs depending on whether the flushing flow target is the mean annual inflow or 1.5 times the mean annual inflow, though this is not shown in Figure 3.9a). Figure 3.9b demonstrates only the results for the latter of these two scenarios (FD scenario and SV operating policy). The intent of Figure 3.9b is to displays the results of several different variations of flushing and routing that are not displayed in Figure 3.9a due to space limitations. Note that there is no significant sedimentation-based downward trend in energy generation over the 100-year simulation horizon at LSS2 or the alternatives. First, this is because sedimentation does not significantly impact storage capacities during the 100-year horizon. Second, this is because the considered reservoirs are assumed to maintain run-of-river operations, which reduces the likelihood that sedimentation will impact energy production in comparison to a storage reservoir. A run-of-river reservoir maintains a relatively small active

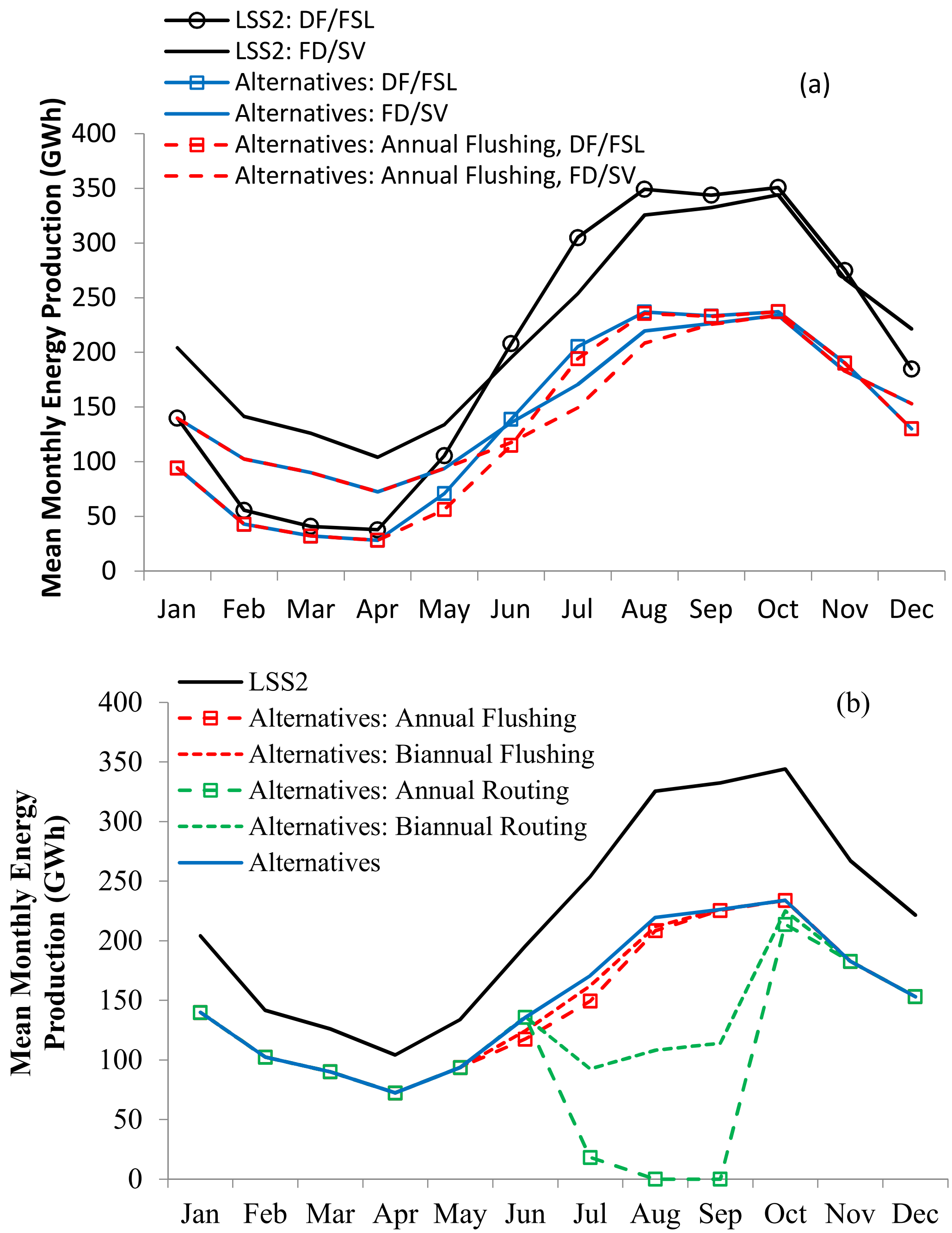


Figure 3.9: Simulated mean monthly energy production at the currently proposed Lower Se San 2 (LSS2) Dam, and combined energy production at alternative dams Lower Se San 2-II (LSS2-II), Lower Sre Pok 2 (LSP2), and Se San Upstream 1 (US1), with and without sediment management implemented. Figure 3.9a plots energy production at LSS2 and alternatives (including annual flushing) for two hydrologic inflow scenarios: (1) DF scenario with FSL system operating policy, and (2) FD scenario with SV operating policy. Figure 3.9b plots only the latter hydrologic inflow scenario (FD, SV), but demonstrates energy losses for several different forms of sediment management. All results are for cases in which the flushing discharge target is equal to the mean annual inflow (MAF).

storage capacity, passing inflows through the reservoir and maintaining a high head. Conversely, a storage reservoir relies on access to a larger active storage capacity, which increases the likelihood that sedimentation will reduce the reservoir's ability to carry over water between seasons or years.).

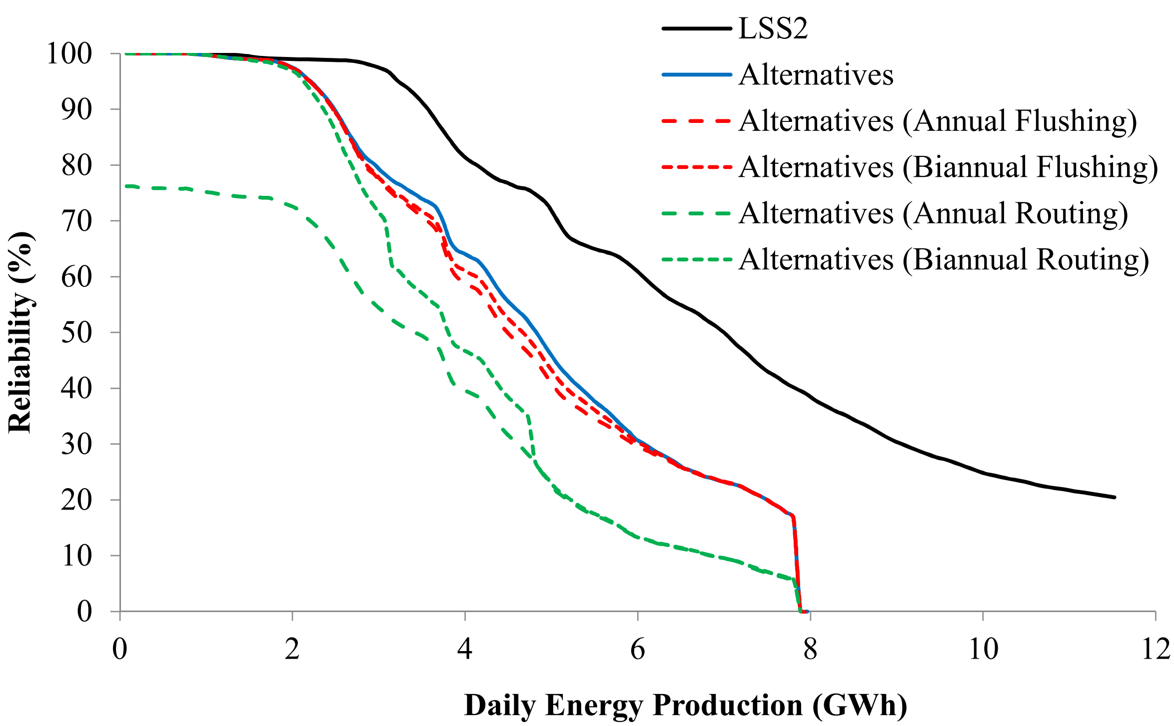
The sediment management strategies proposed here have two important implications for hydropower production. First, replacing the planned 1,793 10^6 m^3 LSS2 reservoir with three smaller reservoirs totaling 627 10^6 m^3 (a 65% reduction in storage capacity) results in reduced head, and therefore a 30% reduction in installed capacity (336 MW instead of 480 MW). Second, specific sediment management practices such as flushing and routing further reduce hydropower production, as a result of energy production lost during the drawdown, flushing and refill phases of sediment management during which generators are offline.

For alternative reservoirs flushed annually, LSS2 mean annual energy production is reduced by 830 GWh (31%), but reduced head and generating capacity at the alternatives is responsible for about 92% of the loss, whereas flushing is responsible for the remaining 8%. Conversely, bi-annual flushing (alternating or non-alternating) is responsible for about 4.5% of the reduced energy production in those respective scenarios. Conversely, annual and bi-annual routing produce much more significant energy losses, but the routing process is responsible for a much larger fraction of these losses than in flushing scenarios. For alternative reservoirs at which annual routing is conducted, LSS2 mean annual energy production is reduced by 1450 GWh (55%), but reduced head and generating capacity at the alternatives is responsible for only 58% of the loss, whereas routing is responsible for the remaining 42%. Conversely, bi-annual flushing (alternating or non-alternating) is responsible for about 27% of the 1140 GWh reduction energy production in biannual scenarios.

Flushing avoids significant losses in annual energy generation because the process is conducted relatively quickly over the course of 2-3 weeks, with some energy production possible during the initial stages of drawdown, as well as during some of the refill stages. Most of the energy losses during flushing occur during the drawdown phase, which takes 7 days on average at the alternative reservoirs considered here, versus the 3-4 days for actual flushing. Importantly, flushing also does not result in significant effects on within-year energy production at the alternative reservoirs. This is because the reservoirs are relatively small in comparison to the mean annual inflow, and can thus be reliably refilled each year after flushing, particularly given that flushing is scheduled during a time period when rainfall and runoff are beginning to increase sharply. More severe consequences associated with failure to refill, or significant duration to refill, would surely occur at a larger storage reservoir.

Flushing affects energy production in several additional ways. First, the energy loss associated with flushing is unpredictable, occurring throughout the time period from June to August whenever the hydrologic conditions for flushing are suitable. The extent of the time horizon over which these flushing losses occur could be more controlled if coordinated releases were initiated by large upstream dams, which may not be feasible in the case of different ownership and operating authority.

Additionally, the reliability of power production is affected by the alternatives proposed here. Figure 3.10 shows the reliability of energy production at LSS2 dam compared to the combined alternative dams (with and without flushing and routing). Much of the alteration in the reliability profile is the result of reduced installed capacity and therefore reduced year-round energy production. Flushing only slightly reduces reliability in comparison to the scenario with no sediment management. This loss comes mostly in the 30-80% reliability range. However, in the 95-100% range, defined here as firm energy, the alternative dam without sediment management, as well as annual and biannual flushing, and biannual routing, do not significantly impact firm energy. This is largely due to the run-of-river nature of reservoir operations. The impact of routing on energy production reliability is only significant when performed annually, as all generators are offline for a period of three months in this scenario.



.

Figure 3.10: Simulated reliability of energy production at Lower Se San 2 (LSS2) Dam as proposed, as well as for the combined alternatives Lower Se San 2-II (LSS2-II), Lower Sre Pok 2 (LSP2), and Se San Upstream 1 (US1), with and without sediment management implemented.

To reduce the impact of such energy losses, flushing should ideally be coordinated to coincide with any required routine dam maintenance that requires a relatively empty reservoir. The MRC notes that such maintenance is best initiated before the start of the wet season for safety reasons, which would coincide with the dates proposed here [*MRC*, 2009a]. If the dam to be flushed constitutes a major and/or reliable source of energy supply in the grid it feeds, the energy supply deficit associated with flushing could render flushing economically infeasible. However, run-of-river dams like those evaluated in this study are not typically expected to provide base load. Thus, if the dam to be flushed is part of a system of dams operated by a particular developer, it is conceivable that some dams in the system could temporarily increase energy production to compensate for flushing-based energy losses at one dam. (For multipurpose dams, particularly those with water supply objectives, such reoperation of a multiple reservoir system would clearly be challenging). Unfortunately, what complicates the possibility for energy supply coordination in the Mekong basin is that many tributaries have the potential to be developed such that dams in cascades on the same tributary are owned and operated by different entities, with the national governments assuming ownership and operating authority only upon completion of a concession period, which can last for periods of up to 40 years. Alternatively, if the dam to be flushed supplies power into an energy grid that is served by other dispatchable energy sources, it may also be possible to temporarily activate those other energy sources while flushing is performed. Flushing will have the smallest possible impact on energy reliability when it is practiced at a dam that constitutes a relatively small input to an integrated, regional energy grid that is naturally capable of compensating for temporary losses. Energy impacts at dams being flushed will be different depending on the energy production role the dam serves.

4.4 Sediment Management: Impacts on Reservoir Storage Capacity

Figure 3.11a is a time series plot of total reservoir storage capacity at LSS2 compared to the combined storage capacity of the three alternative replacement reservoirs. To place reasonable upper and lower bounds on the possible storage capacity loss at LSS2 and at the combined alternative reservoirs, two scenarios are plotted in each case. For LSS2, an upper plot corresponds to the low sediment inflow scenario, and a lower plot corresponds to the high sediment inflow scenario. Again, no sediment management techniques are feasible at LSS2 as planned. For the alternative reservoirs, an upper plot corresponds to highly effective sediment management (annual flushing or routing that removes most sediment), and a lower plot corresponds to no sediment management (flushing or routing). Figure 3.11b plots only the first 10 years of combined alternative reservoirs' storage capacity for a variety of sediment management scenarios, to enhance the clarity of inter-annual variations in storage capacity, particularly for flushing, which results in large, sudden increases in reservoir storage capacity during sediment removal.

The alternative reservoirs initially reduce storage capacity by 65%. While it is possible that this reduction in initial total storage capacity could ultimately be offset by the ability to maintain reservoir storage capacity in perpetuity through sediment management measures, it does not appear likely that this breakeven point will before about 200 years (at best), which may not be an economically and politically relevant time frame. This is unfortunate from social, environmental and economic perspectives, because 200 years of sediment accumulation in this reservoir alone would prevent 3 billion m^3 of sediments and associated nutrients from reaching the Mekong River, thus ultimately adversely impacting critical ecosystem services (including income generation and food security) downstream provided by the Vietnam Delta, and the Cambodian floodplains and Tonle Sap Lake. For sediment management to be viewed as an economic benefit, the traditional paradigm of economic analysis must be modified such that these costs are considered. Additionally, LMB national governments considering these tradeoffs

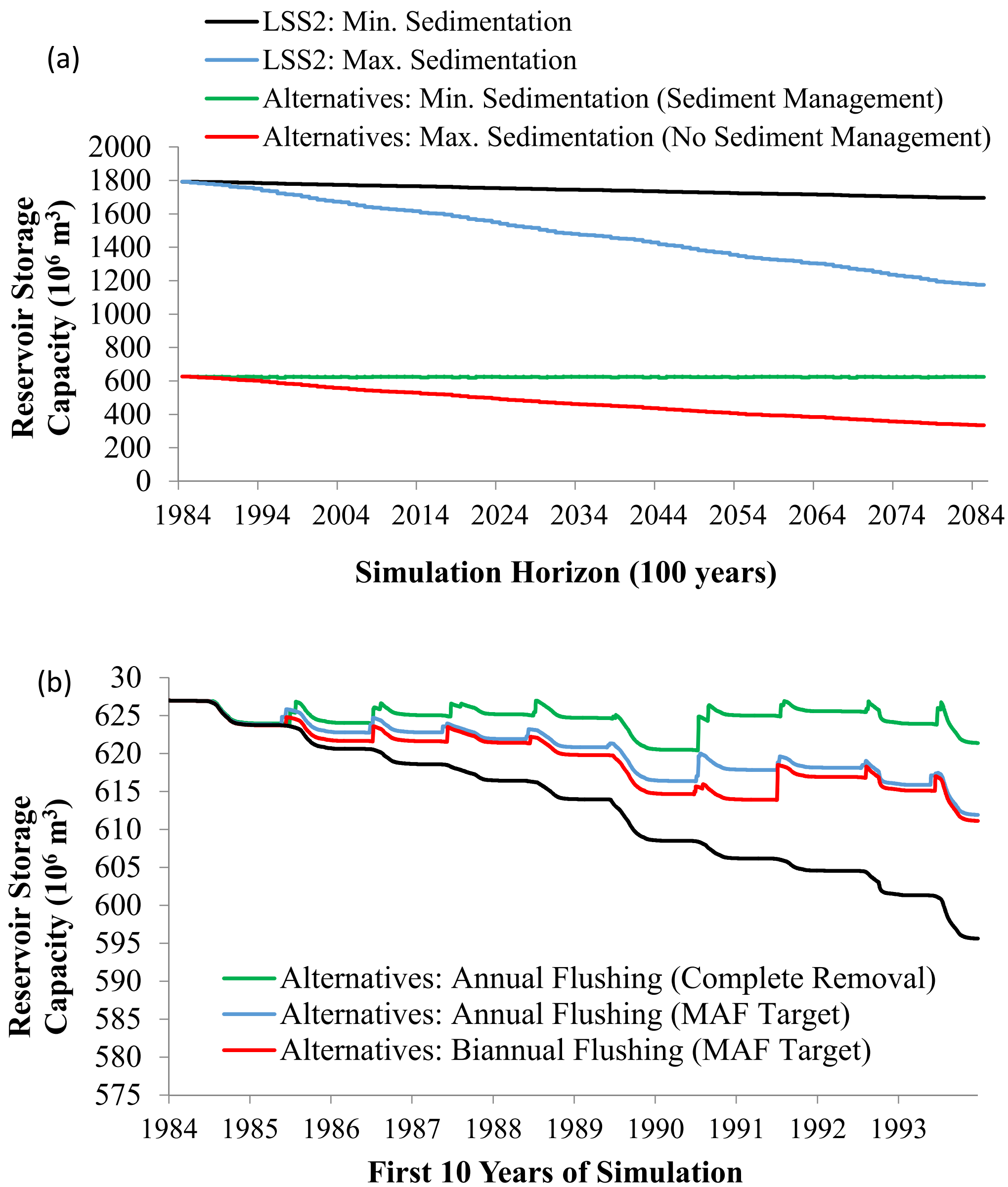


Figure 3.11: (a) Reservoir storage capacity (m^3) during the 100-year simulation horizon for Lower Se San 2 (LSS2) Dam as proposed; and for the combined three alternative reservoirs Lower Se San 2-II (LSS2-II), Lower Sre Pok 2 (LSP2), and Se San US1. To encompass the range of possible storage capacity loss for LSS2 versus the combined alternatives, results for LSS2 are shown for both the high (maximum storage capacity loss) and low (minimum storage capacity loss) sediment inflow scenarios. Results for the alternatives are shown for the high sediment inflow scenario without sediment management (maximum storage capacity loss) and for the low sediment inflow scenario with highly effective annual sediment management (minimum storage capacity loss). In 3.11 (b), the first 10 years of storage capacity loss at the combined alternative reservoirs with and without various forms of sediment management are shown (including flushing with a mean annual inflow (MAF) target), to enhance visibility of inter-annual sedimentation and sediment management effects on reservoir storage-capacity.

will have to weigh the relative importance of sustainability and intergenerational equity, as in the absence of requirements to establish a retirement fund for the dam, future generations will likely bear the costs associated with managing accumulated sediments in an environmentally friendly manner and recovering silted out reservoir sites, of which there are limited viable number [*Morris and Fan*, 1998; *Palmieri et al.*, 2003; *Annandale*, 2013].

4.5 Environmentally Friendly Sediment Management

The sediment management approaches outlined here are not likely to replace energy production from LSS2, in the short-term or long-term. Thus, preserving the Mekong basin's natural sediment balance to maintain associated ecosystem services is more likely to serve as motivation to conduct sediment management than preserving storage capacity. Indeed, *Wild and Loucks* [2014a] demonstrated that this is likely the case for most 3S basins reservoirs. The 3S Rivers host 329 species of fish, or 40% of the Mekong basin's biodiversity [*Baran et al.*, 2013], including 45 endemic species on the Sre Pok River and 24 on the Se San River, two species (*Sinibrama affinis* and *Taxabramis hotayenis*) found in no other part of the Mekong, and five endangered species. Thus, it will be critical to design sediment management techniques capable of removing sediment in an environmentally friendly way, so as not to harm the very ecological features the management approaches are attempting to preserve.

Dams on the 3S rivers, including LSS2, and the alternatives proposed here, would serve as a physical barrier, posing a major threat to fish migration processes in the LMB. While almost half of Mekong fish production (2.1 million metric tons per year) is harvested in Tonle Sap Lake and the Vietnam Delta, at least 39% of this biomass is comprised of long-distance migratory fish. An estimated 89 fish species belonging to 15 families in the 3S basins are migratory [*Baran et* *al.*, 2013], many of which use the 3S rivers as "migration passageways" between the floodplains (production zone) and upstream reproductive zones (e.g., the upper 3S rivers) for spawning and breeding. Researchers are considering possible fish passage designs for LSS2 and other 3S basins dams [*Gätke et al.*, 2013]. However, the sediment management alternatives evaluated here carry an added concern, which is related to the ecological consequences of releasing large quantities of sediment downstream of the LSS2 site over a short period of time.

The simulation results presented earlier suggest that flushing is likely best conducted between May and August, for optimum hydrologic conditions. However, during this time period, as the hydrologic system transitions from the dry season to the wet season, there are expected to be an increased abundance of migratory fish in the vicinity of the dam [*Gätke et al.*, 2013]. Flushing typically results in a sudden increase in sediment concentration that lasts for some time, with discharged concentration typically exceeding 100 g/l, and occasionally exceeding 1000 g/l [*Morris and Fan*, 1998]. The negative impacts of such concentration spikes on fish have been understood, to some extent, since the 17th century, when fish health issues associated with flushing were observed at the Alicante Dam in Spain [*Baran and Nasielski*, 1924].

The diversity of fish species, just in the 3Ss area of the Mekong, will make it very difficult to design optimal sediment and flow releases from dams, as impacts of sediment releases on fish can be physical, chemical, and biological in nature, and affect species differently, as reviewed by *Baran and Nasielski* [2011]. Designing an environmentally friendly sediment management strategy will require considering the upstream and downstream migration patterns of many fish species (including the potential for turbidity and water color to trigger migration responses); their tolerance of various sediment concentrations and durations [*Newcomb and*

MacDonald, 1991; *Newcomb and Jensen*, 1996]; and the sensitivity of the downstream habitat to high sediment loads, particularly on the stream bed, as flushed loads can kill larvae and juveniles, and destroy spawning grounds [*Hesse and Newcomb*, 1982; *Buermann*, 1995; *Brandt and Swenning*, 1999]. At a minimum, concentration standards should be established in advance of implementation of flushing and monitored during flushing so adjustments can be made if necessary. For example, such monitoring has been conducted with success on the Rhone River in France at Genissiat Dam since 1970 [*Fruchart and Camenen*, 2012].

Despite the difficulty of developing a sediment management strategy, some clear lessons emerge from the results presented here regarding how best to conduct flushing for environmental purposes. First, sediment management performed as frequently as possible (i.e., annually) will result in the lowest magnitude sediment releases, and therefore may produce the least environmental impact. Results suggest that even bi-annual flushing produces much higher sediment load variance and mean peak magnitude than annual flushing, which creates conditions to which the aquatic ecosystem is not likely adapted. Additionally, frequent flushing may result in the least severe water quality impacts associated with releases, including detrital organic matter and sediment oxygen demand. While many researchers have noted the negative ecological consequences of flushing, it is noted here that many of the worldwide experiences with flushing of reservoirs has been with dams at which sediment management strategies not initially implemented [*White*, 2001]. At many sites, sediment accumulated for years until flushing was finally implemented, often on an infrequent basis (such as every three years or more). There exists ample opportunity in the Mekong basin to mitigate the impacts of flushing by performing the practice frequently, from the very beginning of dam operations.

The second lesson emerging from the results we present is that flushing as the system transitions into the wet season may provide an opportunity to release sediments as they naturally begin to spike in the system during each year's first big storm events, when the river may have capacity to transport released sediment loads downstream of the dam. Third, environmentally friendly flushing should ensure that there exists a source of clear water to dilute flushed sediment loads [*Fruchart*, 2008]. This typically includes using mid-level outlets to rinse sediment from the downstream channel after flushing is complete. In this study, the site conditions permit alternating the release of sediments from LSS2 (and US1) and LSP2 to dilute the combined concentration released from the system, as well as to provide additional sediment transport capacity to deliver the sediment to the mainstream Mekong River. This is an environmental benefit, and improves energy reliability, as generators at both dams are not taken offline at the same time. Note that the Xe Kong River provides an additional source of water to dilute any sediment loads released by the suggested alternative dams. Fourth, sediment routing would be more environmentally friendly than flushing, as releases are more consistent with natural inflows. However, there will be large energy costs associated with this environmental benefit.

5 Conclusions and Recommendations

Existing and planned reservoirs in the Mekong River Basin are poised to significantly alter the basin's natural sediment regime. Sediment trapped in reservoirs is unavailable to maintain the river's (and its tributaries') geomorphologic structure and support transport of nutrients to productive Mekong ecosystems, which host the second most biodiversity of species in the world. Furthermore, sedimentation presents a serious sustainability and intergenerational equity issue, as it can eliminate the viability (both technical and economic) of reservoir sites, of which there are a limited number, for use by future generations [Annandale, 2013].

Rather than suggesting no dams should be built, we suggest that more benign alternatives to currently proposed dams exist, and the National governments of LMB countries may wish to consider them. We propose a methodology for evaluating the effectiveness of various sediment management-focused changes to reservoir siting, design and operating policies (e.g., sediment flushing), as well as the impact of these changes on hydropower production. Results from applying this methodology to the Lower Se San 2 Dam in Cambodia suggest that the following actions have the potential to significantly improve sediment passage at dams in the Mekong basin:

1. Reducing the size of reservoirs (to reduce trapping and make sediment management possible);
2. Changing the location of reservoirs (e.g., LSS2) such that they will not create sediment trapping in large floodplain areas (e.g., between the Se San and Sre Pok Rivers), which cannot be accessed by incised flushing channels;
3. Installing low level outlets in the dam that permit a reservoir to be completely emptied and permit free passage of flow and sediment for a desired period of time; and
4. Implementing sediment management practices such as flushing and routing, which require changes to reservoir operating policies.

Flushing involves drawdown of a reservoir using low-level outlets, and free-flow conditions through the reservoir for a period of several days. Conversely, drawdown routing involves drawdown of a reservoir throughout the wet season. Sediment flushing practices result in two important impacts. First, energy output is reduced, due mostly to the reduced head at the smaller replacement reservoirs, and to a lesser extent to the effect of flushing, during which time the reservoir is empty and not producing energy. Second, flushing could potentially significantly increase discharge of sediment loads in to the riverine environment downstream of the flushed dam. More frequent flushing, from the very start of reservoir operations, would create the least environmental impact, without significant impacts on firm energy production at a run-of-river dam such as LSS2. Careful attention must be paid to managing the concentration and duration of sediment releases downstream in an environmentally friendly manner, to be sure the diversity of aquatic plant and animal species downstream are capable of withstanding the altered sediment regime. In contrast to flushing, sediment routing appears to offer the opportunity to discharge more sediment and in a way that more closely resembles the river's natural sediment regime, but significant energy losses are likely to occur.

The purpose of this study is to introduce and apply a methodology for evaluating the impacts of various sediment management measures, rather than to provide a complete set of sediment management alternatives for the LSS2 Dam. Thus, future assessments could include evaluation of several other techniques using the tools and methodology presented here, such as sluicing, which would require lowering the height of the existing dam and conducting only partial reservoir drawdown to permit sediment passage during times of high sediment inflow, potentially without required energy outages. Regardless of what alternatives are evaluated here or in future studies, a major limitation of these results is that they do not offer a plan for managing sediment in multiple dams in the 3S basins (e.g., LSS2). If multiple reservoirs decide to conduct sediment management, it will become a significant operational and political challenge to coordinate the efficient release of sediment through cascade of reservoirs, particularly on the transboundary (Cambodia and Vietnam) Se San and Sre Pok Rivers. Lessons about how to implement this in practice in an international river basin can be learned from France, where flushing at the Genissiat Dam is coordinated with operations at the Verbois and Chancy-Pougny Dams in Switzerland [*Fruchart*, 2008]. In Japan, reservoir operations are also coordinated for purposes of Sediment management, such as at Unazuki and Dashidaira Dams [*Kantoush et al.*, 2011].

There are important limitations to the findings presented here. First, while the concept of taking a large dam such as LSS2 and breaking it into several smaller dams [*Annandale*, 2012] is technically feasible, the economic feasibility of this option must be evaluated, as constructing several dams to replace one dam could require costly infrastructure, not to mention that it can create additional fish passage challenges. Second, the observations and suggestions in this paper regarding reservoir operations to achieve flushing are most likely to be applicable to reservoirs and locations that share the following characteristics:

1. **Locations that experience predictable annual wet and dry seasons.** The results presented here are most likely to be applicable to regions of the world that experience seasonal hydrologic inflow patterns similar to those shown in Figure 3.7, which are typical of tropical wet and dry climates [*Pidwirny*, 1999]. Results may also apply to areas in the mid-latitudes where spring snowmelt provides a predictable annual period of peak flows adequate for flushing [*Palmieri et al.*, 2003]. While most reservoir flushing throughout the world is conducted during the dry season, this study demonstrates that Mekong hydrology permits flushing to be conducted after the dry season, during the transitional season before monsoonal flows become too high to empty a reservoir and sustain free-flow conditions through low-level outlets.

2. **Locations on rivers where the channel is relatively narrow.** This allows the cross-sectional geometry of the incised channel formed during flushing to approximate the reservoir's cross-sectional dimensions, thereby maximizing the efficiency of sediment removal.
3. **Smaller reservoirs.** Smaller reservoirs can be safely and quickly emptied, and quickly and reliably refilled each year, without severely impacting reservoir performance with respect to various operational objectives.
4. **Reservoirs that supply energy to an integrated regional energy grid.** The impact of sediment management on energy production at any dam will ultimately depend on the role the reservoir of interest plays in the energy grid it serves. Flushing will have the smallest possible impact on energy reliability when it is practiced at a dam that constitutes a relatively small input to an integrated, regional energy grid that is naturally capable of compensating for temporary losses in energy production (e.g., during flushing). The feasibility of implementing flushing would benefit from consideration of opportunities to develop a more integrated regional energy grid.
5. **Reservoirs with available low- and mid-level outlets.** Retrofitting an existing reservoir with sediment management facilities can be difficult and expensive, so such outlet works should be installed in the dam when constructed.
6. **Locations where downstream aquatic ecosystems are relatively well adapted to periods of high sediment discharge.** Clearly, factors such as the concentration and duration of released sediment, as well as frequency and timing of implementation, must still be carefully managed at such locations.

Future work should first include further evaluation of the methods and alternatives proposed here, particularly with more detailed sediment transport models, which will of course require more detailed data. Such detailed analysis would be restricted spatially to specific sites (such as LSS2), rather than attempting to evaluate the system of 19 reservoirs, as is best conducted with a screening model such as *SedSim*. This will generate improved predictions of the potential improvement offered by various sediment management techniques, as well as more accurate estimates of sediment concentrations released during flushing, particularly on a sub-daily basis, to evaluate potential impacts on ecosystems downstream. Improved data are clearly needed to improve such future sediment management studies, particularly sediment load estimates, grain size distributions, and detailed reservoir operating policies.

Finally, the purpose of developing and evaluating sediment management options is to improve sediment and nutrient discharge to the mainstream Mekong River and Cambodian floodplains to support fishery productivity, and ultimately to reduce the true economic impact of dams. Thus, it will be important to predict the direct impacts of sediment management strategies on ecosystem health and productivity. This will require an improved scientific understanding of the interactions among sediment, nutrients and aquatic species in the Mekong.

6 References

Annandale, G.W. (2012), *A Climate Resilient Mekong: Sediment Pass-Through at Lower Se San 2*, Golder Assoc. Inc., Lakewood, CO, Nat. Heritage Inst., San Francisco, Calif.

Annandale, G.W. (2013), *Quenching the Thirst: Sustainable Water Supply and Climate Change,* CreateSpace, North Charleston, S. C.

Baran, E. and Nasielski, J. (2011), *Reservoir Sediment Flushing and Fish Resources*, Report submitted by WorldFish Center, Phnom Penh, Cambodia to Natural Heritage Institute, San Francisco, CA, December 2011.

Baran E., and E. Guerin (2012), *Fish bioecology in relation to sediments in the Mekong and in tropical rivers*, Report for the Project "A Climate Resilient Mekong: Maintaining the Flows that Nourish Life" led by the Nat. Heritage Inst., WorldFish Cent., Phnom Penh, Cambodia, 52.

Baran, E., S. Samadee, T.S. Jiau, and T.T. Cong (2013), *Fish and fisheries in the Sekong, Sesan and Srepok basins (3S Rivers, Mekong Watershed), with special reference to the Sesan River*, Water and Food Challenge Program in the Mekong, Optimizing the management of a cascade of reservoirs at the catchment level, WorldFish Center, Phnom Penh, Cambodia, 65.

Brandt, S.A. and J. Swenning (1999), Sedimentological and geomorphological effects of reservoir flushing: the Cachi reservoir, Costa Rica, 1996, *Geografiska Annaler* 81, 391-407.

Brune, G.M. (1953), Trap Efficiency of Reservoirs, *Trans. AGU,* 34, 407-418.

Buermann, Y., H.H. Du Preez, G.J. Steyn, J.T. Harmse, and A. Deacon (1995), Suspended silt concentrations in the lower Olifants River (Mpumalanga) and the impact of silt releases from the Phalaborwa Barage on water quality and fish survival, *Koedoe*, 38 (2), 11-34.

Cambodia National Mekong Committee (CNMC) (2009), *Basin Development Plan Programme, Profile Sub-area Se Kong-Se San-Sre Pok in Cambodia*, Phnom Penh, Cambodia.

Clift, P.D., D.L. Graham, and J. Blusztajn (2004), Marine sedimentary evidence for monsoon strengthening, Tibetan uplift and drainage evolution in East Asia, in *Continent and Ocean Interactions with East Asian Marginal Seas*, *Geophys. Monogr. Ser.* 149, pp. 259–282, AGU, Washington, D. C.

Fruchart, F. (2008), Why and how to flush a reservoir without environmental impacts, *Regional Workshop on Discharge and Sediment Monitoring and Geomorphological Tools for the Lower-Mekong Basin*, Vientiane, Lao PDR, 21-22 October 2008, 33.

Fruchart, F., and B. Camenen (2012), Reservoir Sedimentation: Different Type of Flushing – Friendly Flushing, Example of Genissiat Dam Flushing, *International Symposium on Dams for Changing World*, Kyoto, Japan, June 5, 6 pp.

Fu, K.D., and D.M. He (2007), Analysis and prediction of sediment trapping efficiencies of the reservoirs in the mainstream of the Lancang River, *Chin. Sci. Bull.,* 52(Supp. II), 134–140.

Gätke, P., E. Baran, H.M. Fontes Jr., S. Makrakis, M.C. Makrakis, T. A. Rasanen and S. Samadee (2013), *Fish Passage Opportunities for the Lower Sesan 2 Dam in Cambodia – lessons from South America, Project report: Challenge Program on Water & Food Mekong project MK3, Optimizing the management of a cascade of reservoirs at the catchment level*, International Centre for Environmental Management (ICEM), Hanoi, Vietnam.

Gupta, A., and S.C. Liew (2007), The Mekong from satellite imagery: a quick look at a large river, *Geomorphology*, 85, 259-274.

Hesse, L.W. and Newcomb, B.A. (1982), Effects of Flushing Spencer Hydro on Water Quality, Fish, and Insect Fauna in the Niobrara River, Nebraska, *North American Journal of Fisheries Management* 2, 45-52.

Hortle, K.G. (2009), Fishes of the Mekong - how many species are there? *Catch and Culture,* 15, 4-12.

ICEM (2010), Hydrology and Sediment Baseline Assessment Working Paper, in *Baseline assessment report, Strategic Environmental Assessment of hydropower on the Mekong mainstream for the MRC*, pp. 85, Int. Cent. Environ. Manage., Hanoi, Vietnam.

Jansson, M.B., and U. Erlingsson (2000), Measurement and quantification of a sediment budget for a reservoir with regular sediment flushing, *Regulated Rivers: Research and Management*, 16, 279-306.

Junk, W. J., P.B. Bayley, and R.E. Sparks (1989), The flood pulse concept in river-floodplain systems, in *Proceedings of the International Large River Symposium (LARS), Can. Spec. Publ. Fish. Aquat. Sci.*, edited by D. P. Dodge, pp. 110–127.

Kantoush, S.A., T. Sumi, and Y. Takemon (2011), Lighten the load, *International Water Power and Dam Construction*, 38-45.

Kokubo, T., M. Itakura and M. Harada (1997), Prediction methods and actual results on flushing of accumulated deposits from Dashidaira reservoir, in *19th ICOLD Congress*, Q. 74, R. 47, 761–791, Florence, Italy.

Kondolf, G.M., C. Alford, and Z. Rubin (2011), *Cumulative Effects of Tributary Dams on the Sediment Loads and Channel Form in the Lower Mekong River: Progress Report through 30 September 2011*, Dep. of Landscape Archit. and Environ. Plann., Univ. of California, Berkeley.

Kondolf, G.M., Z.K. Rubin and J.T. Minear (2014), Dams on the Mekong: Cumulative Sediment Starvation, *Water Resour. Res., 50* doi:10.1002/2013WR014651.

Kummu, M., and O. Varis (2007), Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River, *Geomorphology*, 85, 275-293.

Kummu, M., X.X. Lu, J.J. Wang, and O. Varis (2010), Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong, *Geomorphology*, 119, 181–197.

Lamberts, D. (2006), The Tonle Sap Lake as a productive ecosystem, *Int. J. Water Resour. Dev.*, 22(3), 481-495.

Liu, J., S. Minami, H. Otsuki, B. Liu, and K. Ashida (2004), Environmental impacts of coordinated sediment flushing, *J. Hydraul. Res.*, 42, 461–472.

Lu, X.X., and R.Y. Siew (2006), Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams, *Hydrol. Earth Syst. Sci.,* 10, 181–195.

Mekong River Commission (MRC) (2009a), *Preliminary design guidance for proposed mainstream dams in the Lower Mekong Basin*, Mekong River Comm., Vientiane, Lao PDR, 38.

Mekong River Commission (MRC) (2009b), *The flow of the Mekong, MRC Management Information Booklet Ser. 2*, Mekong River Comm., Vientiane, November 2009, 12.

Mekong River Commission (MRC) (2010), *State of the Basin Report*, Mekong River Comm., Vientiane, 2010.

Mekong River Commission (MRC) (2011a), *Application of MRC Modelling Tools in the 3S basin*, Mekong River Comm., Vientiane, 2011.

Mekong River Commission (MRC) (2011b), *Basin Development Plan Programme Phase 2: Assessment of Basin-wide Development Scenarios*, Main Rep., Mekong River Comm., Vientiane, April 2011.

Mekong River Commission (MRC) (2012), *Hydropower Project Database*, Basin Development Plan Programme, Mekong River Comm., Vientiane, Lao PDR.

Milliman, J.D., and R.H. Meade (1983), World-wide delivery of river sediment to the oceans, *Geology*, 91, 1-21.

Morehead, M.D., J.P. Syvitski, E.W.H. Hutton, and S.D. Peckham (2003), Modeling the temporal variability in the flux of sediment from ungaged river basins, *Global Planet. Change*, 39(1-2), 95-110.

Morris, G.L., and J. Fan (1998), *Reservoir Sedimentation Handbook*, McGraw Hill, New York.

Newcombe C.P., and D.D. Macdonald (1991), Effects of suspended sediments on aquatic ecosystems, *North American Journal of Fisheries Management* 11 (1), 72-82.

Newcombe, C.P., and J.O.T. Jensen (1996), Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact, *North American Journal of Fisheries Management* 16 (4), 693-727.

Palmieri A., F. Shah, G.W. Annandale, and A. Dinar (2003), *Reservoir Conservation Volume I: the RESCON Approach*, economic and engineering evaluation of alternative strategies for managing sedimentation in storage reservoirs, A contribution to promote conservation of water storage assets worldwide, Int. Bank for Reconstruction and Dev./The World Bank, Washington, D.C., 101.

Pidwirny, M. (1999), *Climatic Regions of the World: Climatology—The geographic study of the atmosphere, Introduction to physical geography II*, Department of Geography, Okanagan University College, http://www.arts/ouc.bc.ca/geog/G121/ln.html, 9.

Piman, T., T. Cochrane, M. Arias, A. Green, and N. Dat (2013), Assessment of Flow Changes from Hydropower Development and Operations in Sekong, Sesan and Srepok Rivers of the Mekong Basin, *Water Resour. Plann. Manage.*, 139(6), 723-732.

Power Engineering Consulting Joint Stock Company (PECC1) (2013), *Sediment Report prepared for Natural Heritage Institute (NHI)*, Hanoi City, Vietnam, 29.

Sarkkula, J., J. Koponen, H. Lauri, and M. Virtanen (2010), *Mekong River Commission (MRC) Detailed Modelling Support (DMS) Project - Origin, fate and impacts of the Mekong sediments*, 53.

Sumi, T., and H. Kanazawa (2006), Environmental study on sediment flushing in the Kurobe River, in *22nd International Congress on Large Dams*, Q.85-R.16, Barcelona, Spain.

Sverdrup-Jensen, S. (2002), Fisheries in the Lower Mekong Basin: Status and Perspectives, *MRC Tech. Pap. 6*, Mekong River Comm., Phnom Penh, 103.

Ta, K.T.O., V.L. Nguyen, M. Tateishio, I. Kobayashi, S. Tanabe, and Y. Saito (2002), Holocene delta evolution and sediment discharge of the Mekong River, Southern Vietnam, *Quat. Sci. Rev.,* 21, 1807–1819.

Walling, D.E. (2008), The changing sediment load of the Mekong River, *Ambio,* 37(3), 150–157.

Wang, G. Q., B. S. Wu, and Z.-Y. Wang (2005), Sedimentation problems and management strategies of Sanmenxia reservoir, Yellow River, China, *Water Resour. Res.*, 41, W09417, doi:10.1029/2004WR003919.

Wang, J.J., X.X. Lu, and M. Kummu (2011), Sediment load estimates and variations in the Lower Mekong River, *Riv. Res. Appl.*, 27, 33-46.

White, W. R. (2001), *Evacuation of Sediments from Reservoirs*, Thomas Telford, London.

Wild, T.B., and D.P. Loucks (2012), *SedSim Model: A Simulation Model for the Preliminary Screening of Sediment Transport and Management in River Basins, Version 3.0: Documentation and User's Manual*, Dep. of Civ. and Environ. Eng., Cornell Univ., Ithaca, New York.

Wild, T.B., and D.P. Loucks (2014a), Mitigating Dam Conflicts in the Mekong River Basin, in *Conflict Resolution in Water Resources and Environmental Management*, edited by K.W. Hipel, et al., Springer, Heidelberg, accepted with minor revisions.

Wisser, D., S. Frolking, S. Hagen, and M. F. P. Bierkens (2013), Beyond peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs, *Water Resour. Res., 49*, 5732–5739, doi:10.1002/wrcr.20452.

Xue, Z., J.P. Liu, D. DeMaster, L.V. Nguyen, and T.K.O Ta (2010), Late Holocene Evolution of the Mekong Subaqueous Delta, Southern Vietnam, *Mar. Geol.*, 269, 45-60.

Ziv, G., E. Baran, I. Rodríguez-Iturbe, and S.A. Levin (2012), Trading-off Fish Biodiversity, Food Security and Hydropower in the Mekong River Basin, *Proceedings of the National Academy of Sciences* 109 (15): 5609-5614.

CHAPTER 4

MITIGATING DAM CONFLICTS IN THE MEKONG RIVER BASIN

Abstract

The Mekong/Lancang River Basin is undergoing a period of rapid hydropower development, with plans to construct over 100 dams in the next several decades. These dams may alter the river's natural flow and sediment regimes, which could significantly degrade the exceptional biodiversity and productivity of the basin's ecosystems. Sediment that is trapped in reservoirs will be unavailable to support the basin's geomorphology and habitats, and by reducing reservoir water storage capacity may decrease hydropower output and reliability. This paper illustrates how alternative dam location, design and operation may have the potential to reduce reservoir sediment trapping. This paper describes the simulation model used to identify alternative siting, design and operating options for two planned dams in Cambodia: Sambor on the Mekong River and Lower Se San 2 on a tributary of the River. Lower Se San 2 Dam is particularly important with respect to biodiversity and ecological productivity. Sambor Dam could prevent significant quantities of sediment from reaching Tonle Sap Lake and the Vietnam Delta, two critically important features of the river basin. Results from daily simulations of water and sediment flows show the extent to which sediment management practices could reduce the adverse impacts of reservoir sediment trapping if conducted in an environmentally friendly manner, as well as the loss in hydropower production resulting from those practices.

1 Introduction

The Mekong/Lancang River flows from the Tibetan Plateau through the Upper Mekong Basin in China (where it is called the *Lancang Jiang*) to the Lower Mekong Basin (LMB), draining parts of Myanmar, Lao PDR, Thailand, Cambodia, and Vietnam. The River discharges into the South China Sea. It has remained largely unaltered for much of its history. Recently, the construction of dams on the mainstream Lancang River, along with dams on tributaries of the Mekong River in the LMB, are signaling future changes in the course of development of this incredibly biodiverse river basin.

The Mekong basin is home to more than 60 million people. Many depend directly on the river and its tributaries as a source of income and food security [*MRC*, 2010]. The river basin is second in biodiversity to the Amazon River Basin. The LMB has an estimated hydropower potential of 30,000 MW, of which only 10% has been developed to date [*MRC*, 2010]. By 2030, the construction of 62 dams, including 6 on the Lancang River and 56 on LMB tributaries, is expected to be completed [*MRC*, 2011b]. Plans exist for a total of 134 dams to be eventually built in the LMB. The extent of river basin development planned to occur over a relatively short span of time warrants an evaluation of the potential impact of the planned development on the temporal and spatial distribution of water and sediment, both of which play critical roles in shaping the river system and maintaining its productivity.

The river's 795,000 km^2 watershed discharges about 460 km^3 of water each year. The climate of the Mekong Basin is controlled by the Monsoon that produces annual wet and dry seasons of approximately equal length [*MRC*, 2005]. The Mekong River is among the world's largest in terms of length and sediment load, delivering approximately 160 million metric tons

(Mt) of suspended sediment per year into the South China Sea [*Milliman and Meade,* 1983].

A major flow and sediment contribution to the mainstream Mekong River, shown in Figure 4.1, is from the Se San, Sre Pok and Se Kong (3S) River Basins. The 3S basins have a contributing watershed area of 78,650 km^2, covering approximately equal parts of Cambodia, Lao PDR and Vietnam. The 3S Rivers have a combined discharge of about 17%-20% of the Mekong River's annual runoff, and likely produce a similar fraction of the LMB sediment load [*Kondolf et al.*, 2011; *Sarkkula et al.*, 2010; *ICEM*, 2010], as well as provide habitats for migrating fish and birds. The 3S Rivers provide fish spawning and breeding grounds to over 40% of Mekong fish species, including 17 species found nowhere else in the world [*Baran et al.*, 2013].

Half of the Mekong basin's annual sediment load is likely generated in the Upper Mekong Basin (China) and the remaining half in the LMB [*Clift et al.*, 2004]. The construction of dams on the Lancang River in China is expected to trap much of the 80 Mt generated annually there [*Lu and Siew*, 2006; *Fu and He*, 2007; *Kummu and Varis*, 2007; *Kondolf et al.*, 2013], with significant trapping potential at dams in the LMB as well [*Kummu et al.*, 2010; *Kondolf et al.*, 2013]. Sediment trapping is not just an issue in the Mekong Basin. Worldwide, reservoir storage capacity is declining due to sedimentation at an estimated average rate of 0.5% to 1% per year [*Mahmood*, 1987; *White*, 2001]. More than 50% of sediment flux in regulated river basins may be getting trapped in reservoirs or other artificial impoundments [*Vörösmarty et al.*, 2003].

Sediments that are trapped in dams are unable to perform two vital functions downstream. First, sediment is needed to preserve the geomorphologic makeup (or physical structure) of the river system downstream that directly influences habitat quality and

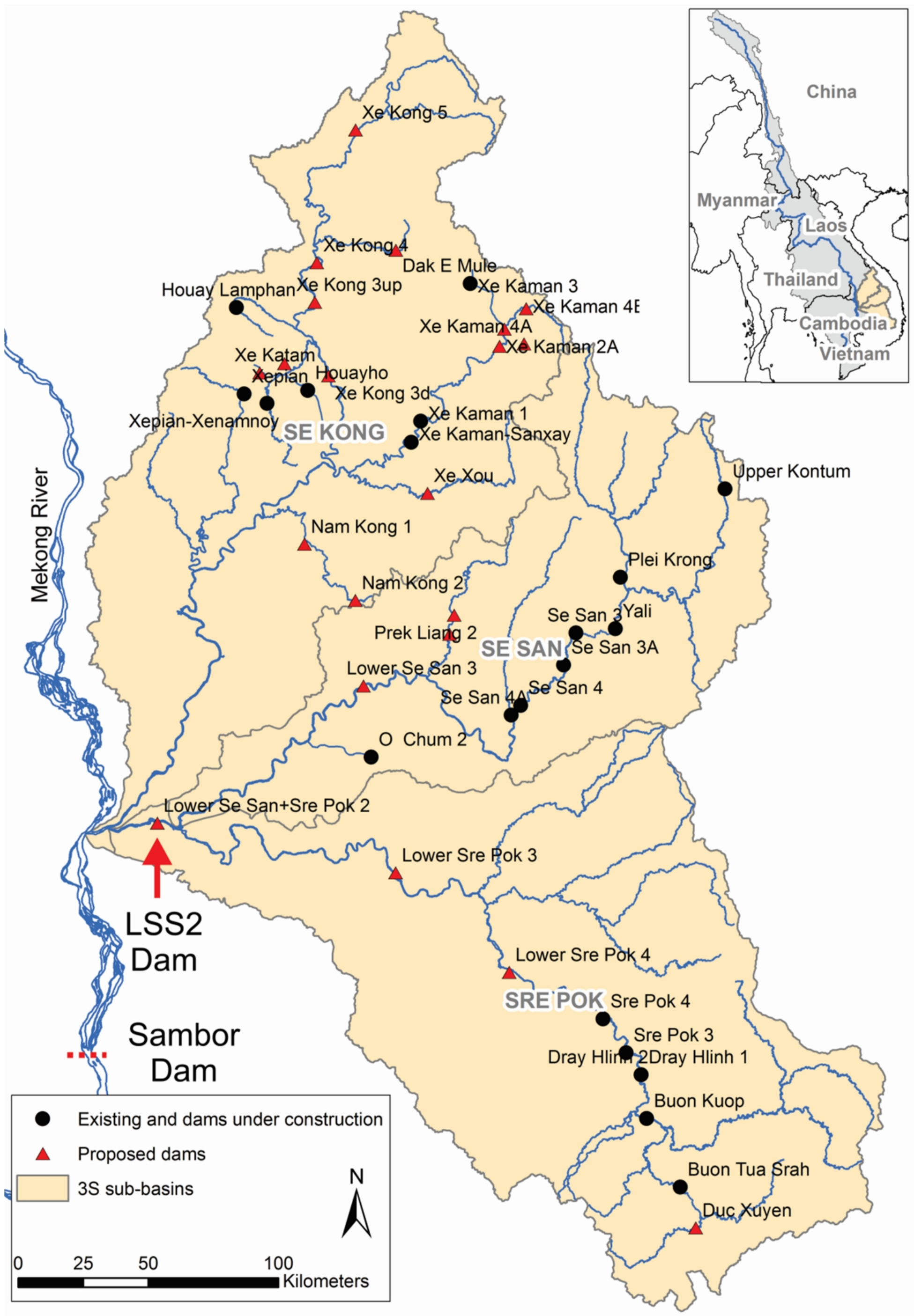


Figure 4.1: Se San, Sre Pok, and Se Kong (3S) tributary basins to the Mekong River, showing current and future reservoir locations[4]. Based on data from *MRC* [2012]. The red arrow indicates the proposed location of the Lower Se San 2 (LSS2) Dam site, whereas the red dashed line indicates the proposed location of Sambor Dam on the mainstream Mekong River.

[4] This figure is reproduced with permission from John Wiley and Sons: Wild, T.B., and Loucks, D.P. (2014), *Water Resour. Res.,* 50, 5141-5157, DOI: 10.1002/2014WR015457.

availability [*Power et al.*, 1996]. In the Mekong basin, this includes the Vietnam Delta, wetlands, the near-shore ocean ecosystem, and floodplain ecosystems. Second, fine sediments (e.g., clay) adsorb and transport nutrients, particularly phosphorus, which play an important role in primary production and floodplain fertility [*Baran and Guerin*, 2012]. In a flood pulse-driven system such as the Mekong River, the exchange of sediment and nutrients between the river and floodplains is responsible for the production of the majority of riverine biomass [*Junk et al.*, 1989; *Sverdrup-Jensen*, 2002; *Lamberts*, 2006]. In this study, sediment passage serves as a surrogate for the potential for ecosystem productivity.

Aside from geomorphologic and nutrient transport issues, sediment accumulation is undesirable from an economic perspective because it reduces reservoir storage capacity, which shortens the reservoir's useful life and flow of future benefits (e.g., power production and flood control); and increases operations and maintenance costs [*Morris and Fan*, 1998]. If a dam fills with sediment and is left in place, the dam site, of which there are a limited number, may be permanently lost for use by future generations, and can become a safety hazard. Conversely, removal of a silted dam can be extremely costly and can lead to the release of large quantities of potentially environmentally harmful accumulated sediments [*Baran and Nasielski*, 2011].

Thus far, relatively little research has been conducted in the LMB regarding the potential impact of reservoir operations on the sediment balance. Previous studies found the potential for as much as 69% of suspended sediment to be trapped throughout the Mekong basin [*Kummu et al.*, 2010], with the potential for trapping to exceed 90% [*Kondolf et al.*, 2013], and as much as 80% of suspended sediment to be trapped in 3S basins reservoirs [*Wild and Loucks*, 2014]. This study evaluates measures that could be taken to reduce such significant sediment accumulation in reservoirs, including alternatives to the siting (location), design (size of reservoir, and availability of mid- and low-level outlets), and operations (e.g., sediment flushing operations) of dams. We identify sediment management practices that are feasible at different planned dam sites; evaluate whether these techniques can improve reservoir sediment outflows without damaging the environmental features the practices are attempting to preserve; and evaluate what losses in typical reservoir function, primarily hydropower production, may be necessary to achieve the improved sediment passage.

Decision makers in the LMB are facing an extremely difficult challenge in shaping the development paths of their respective countries, especially in the less developed nations of Lao PDR and Cambodia, where rapid economic development is internally viewed as imperative. Water is often the most abundant, valuable natural resource in LMB countries, which makes hydropower a particularly attractive energy option. This energy could nurture economic development and be exported for profit. At the same time, 80% of the populace relies on fish and other aquatic animals as a primary protein source and 50% rely on these animals for income [*MRC*, 2010]. The fish are directly dependent on the health of the riverine ecosystems that hydropower production could adversely impact. Each country's fate will be determined in part by the decisions taken with respect to these tradeoffs. Rather than arguing no dams should be built, the sediment management options discussed in this paper acknowledge that dams will be built, but suggest that more benign (with regard to sediment) alternatives to many of the currently proposed dams exist and should be considered.

This paper examines sediment management alternatives as a means of reducing conflicts, hopefully providing an acceptable outcome for all stakeholders in the basin. We are concerned about all the dams being constructed or planned in the basin, but for the purposes of this discussion we will focus on Lower Se San 2 (LSS2) Dam in the 3S basins and Sambor Dam on the mainstream Mekong River. Both are in Cambodia, but have the potential of impacting Vietnam as well.

At the LSS2 Dam site, full drawdown sediment flushing appears to be the best option for reducing sediment trapping [*Annandale*, 2012a]. The LSS2 Dam is important because it could reduce basin-wide fish biomass production by over 9 percent [*Ziv et al.*, 2012], which is the highest potential among tributary dams. Additionally, LSS2 could be constructed within the next five years. Thus, identification and evaluation of opportunities to increase sediment passage through the reservoir, while maintaining significant energy production at the site, is of current interest.

At Sambor Dam, both flushing and sediment bypassing could reduce sediment trapping. Sambor Dam is perhaps the most important proposed dam in the entire basin. Its proposed location at the bottom of the basin could result in sediment and nutrient reductions for two of the basin's most important features that rely on sediment: Tonle Sap Lake (in Cambodia) and the Vietnam Delta. Tonle Sap Lake is one of the most productive freshwater fisheries in the world. The Vietnam Delta produces significant quantities of rice and fish, and hence affects the lives of millions of people. Additionally, the potential for Sambor to trap significant quantities of sediment could discourage efforts to pass sediment through dams throughout the basin upstream. (The same is true of all the dams on the Se San and Sre Pok Rivers upstream of LSS2). Finally, the proposed Sambor Dam would be the most downstream dam sited on the mainstream Mekong River, and as such would be positioned to severely disrupt fish passage, particularly for long-distance migratory species, thereby reducing LMB total fish biomass [*Dugan*, 2008; *Baran and Myschowoda*, 2009; *Baran*, 2012]. A natural sediment and fish bypass system, if successful, could greatly reduce the impact of Sambor Dam on the LMB fishery.

2 Sediment Management Options

Before discussing the sediment management alternatives for LSS2 and Sambor in more detail, it is useful to review the array of reservoir sediment management options available to better understand how sediment flushing (at LSS2 and Sambor) and sediment bypassing (at Sambor) fit in among the range of available techniques. ([*Annandale*, 2013] and [*Morris and Fan*, 1998] provide diagrams and pictures of these techniques).

A variety of options are available for managing sediment in reservoirs, and they generally fall into three categories: minimizing sediment inflow (e.g., catchment management), preventing inflowing sediment from settling by hydraulically routing sediment beyond the reservoir (sediment routing), and removing sediment after it settles (sediment removal) [*Morris and Fan*, 1998]. Catchment management is not considered here because the goal of this study is to evaluate methods that could permit conveyance of the basin's naturally high sediment load. Sediment routing is advantageous in comparison to sediment removal in that regularly performed routing is more likely to produce reservoir sediment outflows that are consistent in timing and concentration with the natural sediment inflow regime.

Sediment routing is generally performed in one of two ways: sediment bypassing or sediment pass-through (e.g., sluicing). Both are typically performed during high flow conditions (e.g., during the monsoon season). Sediment bypassing, the option proposed for Sambor Dam, routes the sediment-laden water around the reservoir to prevent deposition in the reservoir. Sediment pass-through routes the water through the reservoir by maintaining a high sediment transport capacity. Both are implemented during high flow events when the majority of the annual sediment load is transported. Examples of bypassing include bypass tunnels (e.g., the Miwa Dam bypass system in Japan), river modification (e.g., Nagle Reservoir in South Africa), and off-channel reservoir storage (e.g., Fajardo Dam in Puerto Rico) [*Annandale*, 2013].

Flushing can also be done in two ways: full drawdown flushing or partial drawdown flushing. Only full drawdown flushing is considered here, wherein water levels are reduced in the reservoir enough to permit free flow conditions through the low-level outlets. Flushing practices vary considerably among sites, but there exist some commonalities [*Morris and Fan*, 1998]. Flushing is typically performed during lower flow conditions, such as during the very beginning of the wet season, and for a short period of time (e.g., a week or less). From an operational standpoint, performing flushing at this time of year (1) reduces the difficulty and length of time required for drawdown because inflows are low, and (2) increases the likelihood of rapid reservoir refill (and therefore resumption of normal reservoir operations). Low reservoir water levels must be maintained during the flushing period to create high scouring velocities and retrogressive erosion. After flushing, the reservoir is refilled and normal operations are resumed. Drawdown flushing has been practiced at numerous reservoirs throughout the world (e.g., Cachi Dam in Costa Rica, Gebidem Dam in Switzerland, and Sefid-Rud Dam in Iran). Flushing is more likely than routing to adversely impact the environment, as releases typically result in a sudden increase in sediment concentration. Associated impacts on fish species can be physical, chemical, and biological in nature, and are reviewed by Baran and Nasielski [*Baran and Nasielski*, 2011]. Concentration and duration of flushing flows have been shown to be important factors in the potential severity of flushing impacts [*Newcombe and MacDonald*, 1991; *Newcombe and Jensen*, 1996].

3 Simulating Flow and Sediment in the Mekong Basin

3.1 Modelling Approach

Since 1990, many hydrologic models have been used to simulate water flows in the Mekong basin [*Johnston and Kummu*, 2012]. Unfortunately, none possessed the features needed to predict in relative terms the spatial and temporal accumulation and depletion of sediment in river channels and in reservoirs under different reservoir operating and sediment management policies. Hence we developed a daily simulation model, called *SedSim*, to evaluate the performance of specific sediment management techniques (e.g., flushing, sluicing, density current venting, bypassing and dredging) in networks of reservoirs and channels [*Wild and Loucks*, 2012b]. This information is used to identify the relative tradeoffs between hydropower production, and flow and sediment regime alteration, associated with these sediment management techniques. It serves as a means of identifying the more promising sediment management alternatives that can be evaluated in more detail using more detailed and hence more data-intensive models.

In this study, 21 years of average daily reservoir inflows are generated from a calibrated Soil and Water Assessment Tool (SWAT) model [*MRC*, 2011a]. *SedSim* is used to simulate sediment production, transport and trapping, as well as reservoir operations and channel routing. The data required to conduct simulations with *SedSim* were generated by other researchers and institutions. Reliable Mekong basin sediment data useful for generating daily sediment loads are not widely available [*Walling*, 2005, 2008; *Wang et al.*, 2011], so estimates of annual sediment production were obtained from Kondolf et al. [*Kondolf et al.*, 2011, 2013], and converted into daily sediment loads using sediment-flow rating curves [*Milliman and Meade*, 1983; *Morehead et al.*, 2003]. In setting parameter values we benefited from the work of *Walling* [2009] and *Wang et al.* [2011]. Planned reservoir and dam characteristics and operating policies were obtained from MRC [*MRC*, 2011a, 2012] and Piman et al. [*Piman et al.*, 2013]. Data regarding potential alternative dam configurations were obtained from Annandale [*Annandale*, 2012a, 2012b].

3.2 Sediment Management Alternatives

Sediment management measures will be very difficult to successfully implement at the currently proposed dam sites of LSS2 and Sambor (Figure 4.1). Both reservoirs, as proposed, are too long and wide (being located in floodplains) for most sediment management practices to be feasible, and thus will trap large quantities of sediment. Alternative locations and design configurations for these dams could improve their sediment passage characteristics and make sediment management possible [*Annandale*, 2012a, 2012b]. Specifically, relocating the dams to nearby but narrower sections of the river would permit sediment flushing, as flushing is most likely to be successful in a relatively narrow reservoir whose cross-sectional dimensions approximate the dimensions of the incised channel formed during flushing. Additionally, reducing reservoir size (volume and length) not only reduces a reservoir's sediment trapping efficiency, but also increases the likelihood that sediment flushing will be feasible, given that the reservoir must be emptied of water before flushing can proceed, and must be refilled with water before normal operations can resume. Finally, building low-level outlets into the dam would

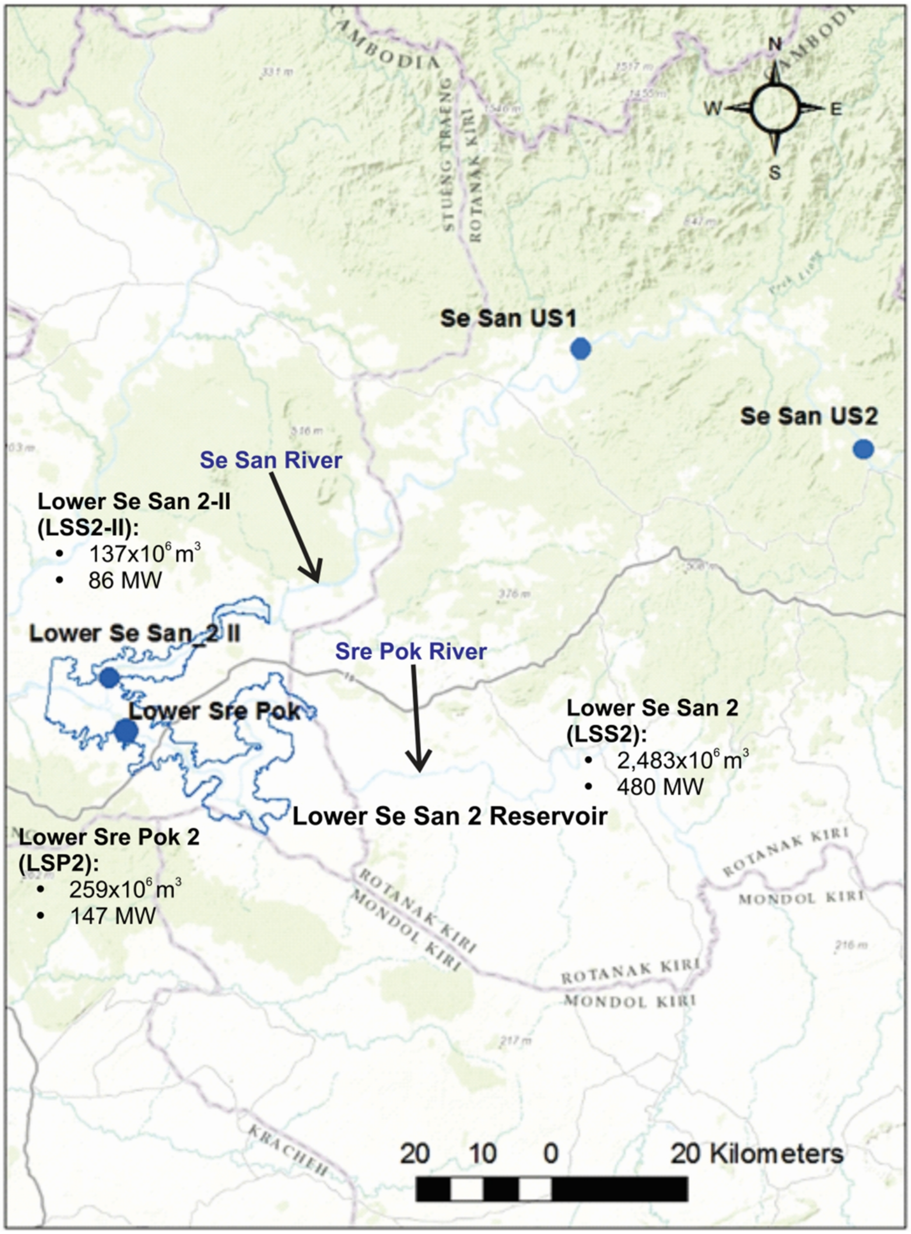


Figure 4.2: Diagram of the currently proposed Lower Se San 2 (LSS2) Dam, which is proposed to be constructed at the confluence of the Se San and Sre Pok Rivers, and two smaller alternative dams that this study proposes should be considered: Lower Se San 2-II (LSS2-II) and Lower Sre Pok 2 (LSP2). LSS2-II and LSP2, marked by blue circles, are proposed within the bounds of LSS2 reservoir as currently planned. Reservoirs Se San US1 and Se San US2, also marked by blue circles, are two additional alternative reservoirs that could be sited upstream on the Se San River to make up for the losses in energy generation that would be associated with not building LSS2 as planned. Proposed reservoir storage capacity (m^3) and power plant installed capacity (Megawatts, MW) are provided for LSS2, LSS2-II and LSP2. Figure adapted from *Annandale* [2012a].[5]

[5] Figure is adapted from Annandale, G.W. (2012a), *A Climate Resilient Mekong: Sediment Pass Through at Lower Se San 2*, Golder Assoc. Inc., Lakewood, CO, Nat. Heritage Inst., San Francisco, CA.

enable flushing, and indeed is a requirement for flushing to be feasible at a dam site.

Figure 4.2 shows the alternative of replacing the currently proposed LSS2 dam with two smaller dams. The Lower Se San 2-II (LSS2-II) Dam on the Se San River, and Lower Sre Pok 2 (LSP2) Dam on the Sre Pok River could be frequently flushed. Figure 4.3 shows the alternative of replacing the currently proposed Sambor Dam with a smaller, narrower reservoir that can be frequently flushed and that would be fitted with a natural sediment bypass channel (using existing braided river channels on the East section of the main river channel). The sediment bypass would direct high sediment loads around the reservoir during the monsoon season and also serve as a natural fish passage system. The currently proposed Sambor Dam would prevent passage of numerous migratory fish species and submerge important fish breeding areas, resulting in potentially severe adverse impacts on the Mekong fishery [*Campbell*, 2009]. While Sambor Dam as currently planned could include fish passage structures (e.g., ladders), such structures may achieve limited success compared to a natural channel, because these structures must be tailored to meet the needs of specific species, of which there are many in the lower portion of the LMB. Bypassing is assumed to occur during monsoonal flows, or those flows in excess of twice the mean annual inflow (27,600 m^3/s). During this time, the portion of flow entering the upstream end of the reservoir site in excess of 27,600 m^3/s is bypassed along with an identical portion of the suspended sediment load.

Several modeling assumptions regarding flushing and bypassing should be mentioned. Flushing at each site is assumed to proceed for four days, beginning around the time of year when the reservoir inflow first exceeds the mean daily unregulated inflow.

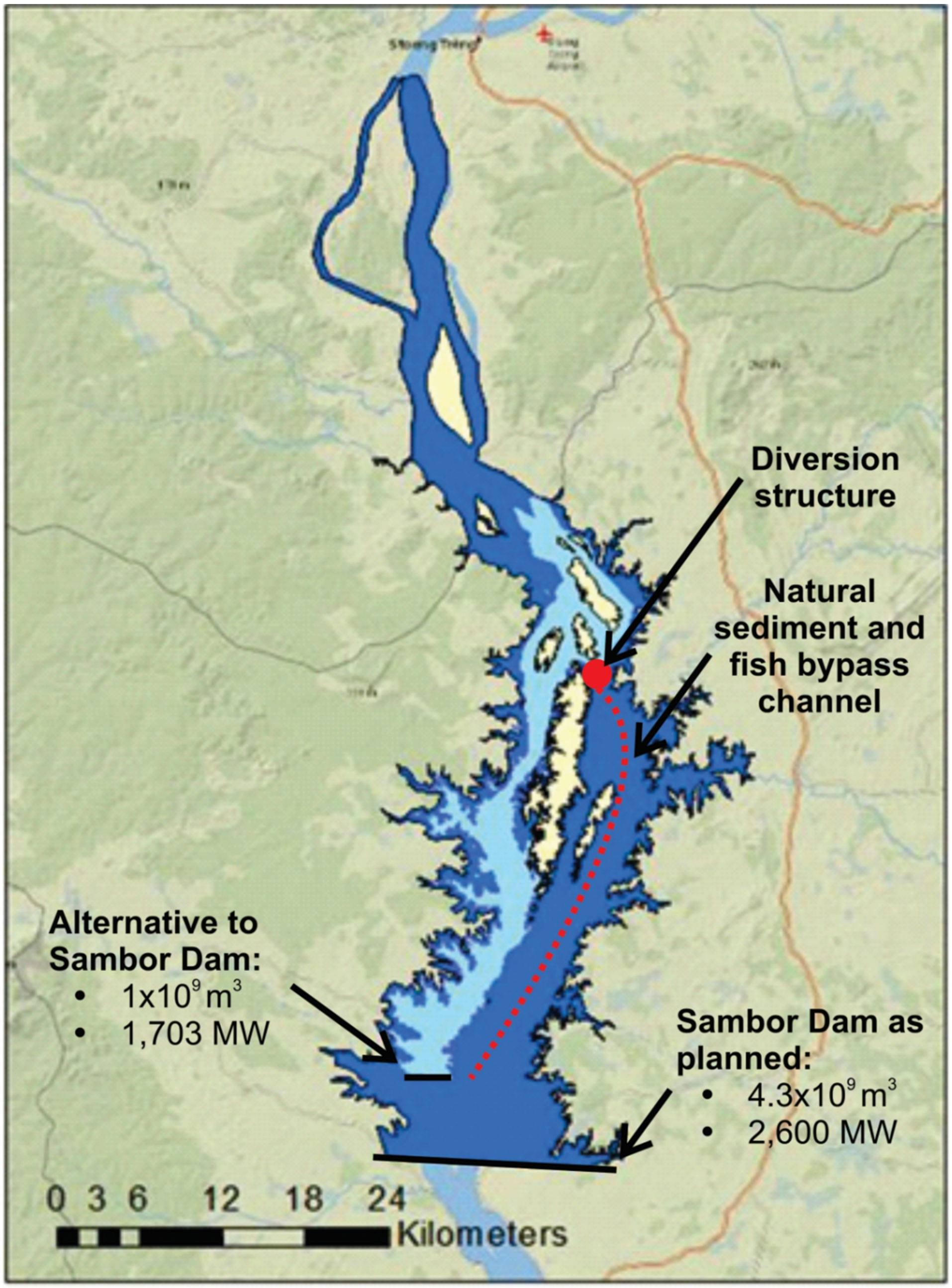


Figure 4.3: Diagram of the currently proposed Sambor Dam and smaller alternative dam on the Mekong River. The alternative reservoir, appearing in lighter blue, would be sited within the bounds of the currently planned reservoir, which appears in a darker blue. The red dashed line indicates the location of the natural sediment and fish bypassing channels on the East of the alternative site, and the red dot indicates the location of a diversion structure that would direct flow and sediment into the diversion channel. Proposed reservoir storage capacity (m^3) and power plant installed capacity (Megawatts, MW) are provided for the proposed and alternative Sambor Dam. Figure adapted from *Annandale* [2012b][6].

[6] Figure is adapted from Annandale, G.W. (2012b), *A Climate Resilient Mekong: Sediment Pass-Through at Sambor Dam*, Golder Assoc. Inc., Lakewood, CO, Nat. Heritage Inst., San Francisco, Calif.

This unregulated mean daily inflow rate is assumed to be the target flushing discharge rate. Flushing a reservoir with this flow rate produces a reasonable long-term sustainable storage capacity (greater than 35%), but is not too large for reasonably-sized low-level outlets to empty the reservoir and discharge flow during flushing without ponding above the outlets. For flushing to be considered successful in a given day, the water surface elevation is required to be maintained to near the original river bed elevation (this is the optimal location of the low-level outlets), and flow is required to equal or exceed 95% of the mean unregulated daily inflow. Drawdown is initiated when the inflow reaches the average unregulated daily value. This approach avoids drawing down a reservoir before inflows are high enough to satisfy flushing discharge requirements, which could result in substantial and uncertain hydropower losses. The quantity of sediment removed during a particular flushing event is determined in each time step using the Long Term Capacity Ratio (LTCR) [*Atkinson*, 1996], which estimates the fraction of a reservoir's initial storage capacity that can be maintained in perpetuity by implementing flushing.

To define the range of possible tradeoffs between sediment and hydropower for the possible alternatives, five LSS2 scenarios were considered and six Sambor scenarios were considered. Aside from the unregulated basin scenario, simulations of LSS2 assume the future condition in which the Sre Pok River and Se San River are developed to the maximum extent that is currently planned (19 dams upstream of the LSS2 site, as seen in Figure 4.1). While 14.3 Mt/yr of sediment is generated upstream of LSS2, only 7 Mt/yr reaches LSS2 due to upstream trapping. Simulations of Sambor Dam and alternatives assume the basin upstream of Sambor is developed to the extent of the MRC definite future development scenario [*MRC*, 2011b], or 47 existing and planned dams. While 156 Mt/yr of sediment is generated upstream of Sambor, only

80 Mt/yr reaches Sambor due to upstream trapping [*Kondolf et al.*, 2013].

The five LSS2 scenarios were as follows:

1. Unregulated 3S basins (no reservoirs).
2. Currently proposed Lower Se San 2 (LSS2).
3. Alternatives Lower Se San 2-II (LSS2-II) and Lower Sre Pok 2 (LSP2). No flushing.
4. Alternatives LSS2-II and LSP2. Annual flushing.
5. Alternatives LSS2-II and LSP2. Biannual flushing (every two years), both reservoirs being flushed during the same year.

The six scenarios considered for the Sambor alternatives are listed below. Compared to LSS2, flushing frequency is not varied for the Sambor alternative because the results of varying flushing frequency at Sambor are similar to the results shown for LSS2-II and LSP2.

1. Unregulated Mekong Basin (no reservoirs constructed upstream of Sambor).
2. Currently proposed Sambor Dam without sediment management.
3. Alternative Sambor Dam without sediment management.
4. Alternative Sambor Dam with annual flushing.
5. Alternative Sambor Dam with a sediment bypass channel.
6. Alternative Sambor Dam with a sediment bypass channel and annual flushing

4 Results and Discussion

Presenting a comprehensive assessment of the tradeoffs between sediment passage and hydropower production is difficult because the tradeoffs occur over different time scales. For example, the results here will focus on tradeoffs between annual and mean monthly sediment loads and energy production, whereas in reality many other time scales and measures are just as important for sediment, energy and indirectly, biodiversity.

Beginning with LSS2 at the annual time scale, Figure 4.4 demonstrates the potential impact of LSS2 Dam as currently planned, as well as the potential improvement in sediment passage that could be achieved by implementing sediment management practices. Aside from the regulated and unregulated sediment inflow to the LSS2 site, Figure 4.4 includes cases in which 1) LSS2 is built as planned, and 2) LSS2 is divided into two smaller reservoirs (LSS2-II and LSP2), without any form of sediment management implemented. The purpose of Figure 4.4 is to highlight what potential impact any form of sediment management (e.g., flushing) could have if implemented.

Figure 4.4 illustrates several important points. First, the unregulated sediment load at the LSS2 site will be significantly reduced due to trapping by the 19 reservoirs expected to be constructed upstream. The simulated effect of the upstream reservoirs is to reduce the mean annual sediment inflow to the site by 51% (from 14.3 Mt/yr to about 7 Mt/yr). The proposed LSS2 reservoir would then trap 77% of the remaining load on average, reducing the annual discharged load from 7 Mt/yr to 1.6 Mt/yr. While the significant difference between unregulated inflow and sediment outflow for each management scenario is largely driven by the trapping of sediment in the 19 reservoirs upstream, in the absence of extensive upstream reservoir development, LSS2 would still have the potential alone to trap much of the sediment expected to be trapped in reservoirs upstream, given its high average trapping efficiency of 77%.

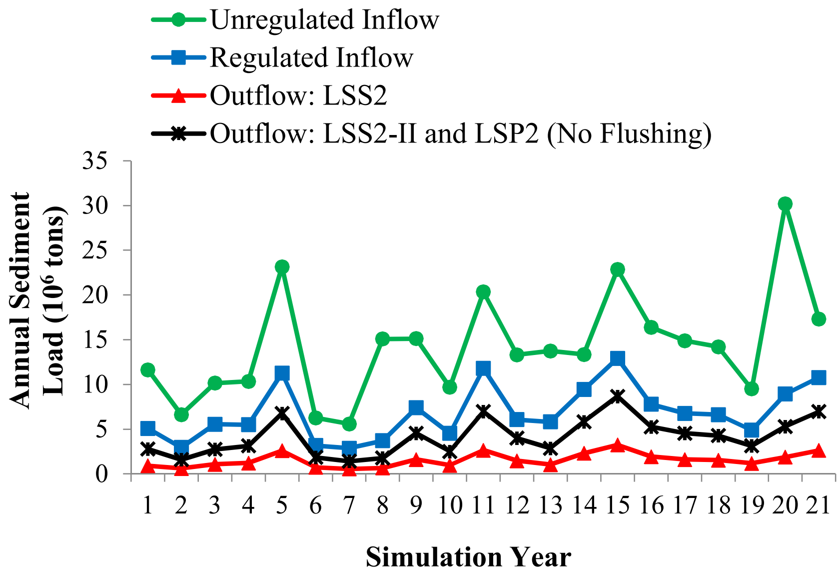


Figure 4.4: Simulated annual sediment load (10^6 tons) inflows and outflows for 21 years for the currently proposed Lower Se San 2 (LSS2) Dam site, and for two alternative dams, Lower Se San 2-II (LSS2-II) and Lower Sre Pok 2 (LSP2), excluding flushing practices. The outflow time series corresponding to LSS2-II and LSP2 are combined into one time series.

To increase the discharged load from 1.6 Mt/yr to a value that more closely resembles the inflow, LSS2 could be replaced with two smaller reservoirs: LSS2-II and LSP2. The combined effect of the smaller two dams would be to reduce the average trapping efficiency from 77% (LSS2) to 40%, which would reduce the trapped load from 7 Mt/yr to 4.1 Mt/yr. This is more than a 150% increase in annual sediment load discharge compared to LSS2. This improvement is attributed only to reservoir resizing and relocation, which naturally reduces sediment trapping without implementing any sediment management techniques. Appropriate sediment management practices have the potential to produce additional increases in sediment discharge (i.e., to produce an annual sediment load time series that lies somewhere between the middle two time series in Figure 4.4).

If LSS2 is constructed as planned, approximately 18% of its 2.5 billion m^3 storage capacity would be lost to sedimentation after 100 years, assuming an average bulk density of

1200 kg/m^3 for deposited sediment [*Xue et al.*, 2010]. Thus, the potential ecological benefit of increasing sediment discharge through the LSS2 site is more likely to serve as motivation for conducting sediment management than a desire to mitigate impacts on long-term energy production. However, if the Sre Pok and Se San basins are ultimately developed to a lesser extent than expected (i.e., if fewer than 19 of the planned dams upstream of LSS2 are constructed), sedimentation at LSS2 could increase significantly, thereby increasing the likelihood of long-term energy production impacts if sediment is not managed.

Having described the potential for sediment management to improve sediment flows downstream of the LSS2 site, Figure 4.5 demonstrates the impact that specific management techniques could have on the sediment regime downstream. This figure focuses on mean monthly sediment loads, instead of annual sediment loads, because the monthly time scale reveals that sediment management methods such as flushing can alter the seasonal distribution of sediment loads. This in turn may have important ecological consequences.

Figure 4.5 demonstrates that the currently proposed LSS2 Dam will significantly reduce the regulated sediment load inflow at the LSS2 site, despite the significant trapping that will already take place in upstream reservoirs. (The upper-most time series in Figure 4.5, which represents the unregulated inflow into the site, does not serve as sediment inflow in the simulations used to create the sediment outflows in Figure 4.5. Rather, the regulated time series represents the inflow pattern used to produce the simulation results). The combined mean monthly sediment outflow from the smaller two reservoirs (LSS2-II and LSP2), without any sediment management implemented, is a clear seasonal improvement to the proposed LSS2. Figure 4.5 demonstrates that annual and biannual flushing could further increase sediment passage at the alternative sites.

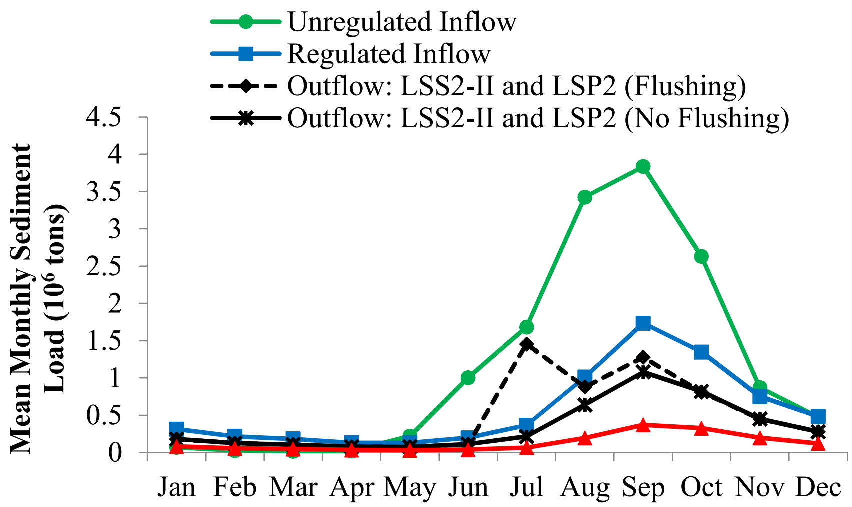


Figure 4.5: Mean monthly sediment load (10^6 tons) inflows and outflows at Lower Se San 2 (LSS2) Dam site. All outflow time series result from the regulated inflow time series. This demonstrates the simulated potential for alternative reservoirs Lower Se San 2-II (LSS2-II) and Lower Sre Pok 2 (LSP2), combined with flushing, to improve sediment passage compared to current plans for LSS2. The outflow time series corresponding to LSS2-II and LSP2 are combined into one time series for comparison to LSS2. Annual and biannual flushing produce similar mean monthly sediment outflows, so they are represented by the same time series.

Flushing significantly increases sediment load discharge compared to the currently proposed LSS2 and to the alternatives LSS2-II and LSP2 without any sediment management implemented. However, the extent to which this increased sediment discharge represents an improvement depends on the time scale of interest. In general, annual sediment loads, which are not shown here, are significantly increased as a result of the alternative configurations and sediment management practices. This represents a major improvement to the integrity of the geomorphologic system. For example, annually flushing LSS2-II and LSP2 results in a reduction in mean annual sediment load of only 16% compared to the regulated inflow (i.e., 5.8 Mt/yr discharge is produce from 7 Mt/yr inflow), meaning that only 16% of the inflowing sediment load is trapped in the two alternative reservoirs. The case in which flushing is performed biannually results in similar average trapping (18%). Importantly, while less frequent flushing has the potential to produce similar long-term mean annual sediment loads to more frequent flushing, the variance in loading associated with less frequent flushing is far less environmentally friendly, producing larger sediment loads when flushing events occur, and at intervals less frequent than the natural annual intervals to which the aquatic ecosystem has likely adapted.

Transitioning now to the monthly time scale, flushing alters the timing and distribution of mean monthly sediment loads. This is primarily because sediment flushing is performed for a short duration of time during periods of relatively lower flows. Thus, all flushing scenarios result in a mean peak sediment load occurring on average two months before the natural mean peak. On average, these values are 300%-400% higher than the mean regulated sediment inflows. However, the flushing spike in mean sediment discharge at the end of the wet season is still enclosed within the bounds of the unregulated mean monthly sediment load inflows. This is an important result because one of the goals of sediment management in this region should be to maintain some consistency with the natural seasonal sediment load regime.

The visible spike in sediment load released from LSS2-II and LSP2 (Figure 4.5) does not exceed the mean monthly unregulated sediment load inflow, but could still be a significant problem if the loads released produce high enough concentrations for a long enough period of time [*Newcombe and MacDonald*, 1991; *Newcombe and Jensen*, 1996]. Additionally, if the downstream channel does not have sufficient capacity to transport the flushed sediment loads downstream of the reservoir, large quantities of sediment may settle in the channel, which can kill larvae and juveniles, and destroy spawning grounds [*Hesse and Newcomb*, 1982; *Buermann*, 1995; *Brandt and Swenning*, 1999]. These issues require further investigation in the Mekong

Basin, as specific impacts will depend on the sensitivity of particular plant and animal species to spikes in concentration and changes in riverine habitats. Previous studies have not assessed such possible flushing impacts on the large diversity of fish species living in the Mekong basin. Ultimately, the environmental impact of flushing will depend on how flushing is implemented in practice. For example, after flushing is completed, clear water should be released from mid-level outlets to wash away flushed sediment that may accumulate in the downstream channel [*Fruchart*, 2008].

It is also useful to assess the implications of conducting sediment management during the wet season, as the annual flood pulse drives the Mekong basin's productivity through the transport of most of the annual flow, sediment and nutrients. Referring to the results of implementing flushing displayed in Figure 4.5, after the two mean monthly sediment peaks in July and August, a second, lower peak then occurs in September. This peak would have occurred in the absence of sediment management (note the similarity in September to the case in which no sediment management is attempted). The 19 reservoirs to be constructed upstream of the LSS2 site would reduce the mean sediment load in the three wettest months (August, September and October) by 58% (9.9 Mt to 4.2 Mt). The currently proposed LSS2 would further reduce the sediment load in the wettest three months by about 79% (from 4.2 Mt to 0.9 Mt). LSS2-II and LSP2 without flushing reduce wet season sediment outflows by only 40% (4.2 Mt to 2.5 Mt). Reductions in the mean sediment inflow (4.2 Mt) in the three month peak wet period are only about 28% when flushing is conducted.

Sediment management measures clearly have the potential to increase sediment discharge downstream of dams in the Mekong basin. However, the sediment management measures proposed here have significant implications for hydropower production. Conducting sediment management has two primary impacts on the sediment regime, and two primary impacts on energy production. Reducing the volume of water storage at the LSS2 site by constructing the two smaller reservoirs, as well as flushing the two smaller reservoirs, creates two sediment impacts: less sediment is trapped, and sediment that is trapped can be removed via flushing. With regard to hydropower, reducing reservoir size, and conducting flushing at those smaller reservoirs, have two primary impacts: smaller reservoirs produce less energy due to reduced operating head and installed capacity, and flushing reduces energy production as generators are taken offline when the reservoir is emptied to conduct flushing. Figure 4.6 highlights these two hydropower impacts by plotting monthly mean energy production for the same scenarios for which the sediment implications are displayed in Figure 4.5. Due to their reduced combined installed capacity (233 MW), LSS2-II and LSP2 are not capable of combining to entirely replace the energy production of the proposed LSS2 (480 MW). The reduced combined generating capacity is responsible for the majority of the 58% reduction in mean annual energy (2,925 GWh to 1,225 GWh) that would result from building LSS2-II and LSP2 instead of LSS2.

There is also a loss in power production associated with flushing. Annually flushing LSS2-II and LSP2 reduces mean annual energy production (compared to not managing sediment in these reservoirs) by only about 4%, whereas biannual flushing results in mean annual reductions of only 2%. Flushing avoids significant losses in annual power generation because the process can be conducted relatively quickly. Thus, flushing alone does not critically impact average annual or monthly power production. This is a significant result because one or two more dams could be constructed upstream of LSS2-II and LSP2 (e.g., Se San US1 and Se San US 2 in Figure 4.2) to continue to replace the installed energy generating capacity that is lost by not constructing LSS2 as planned. While potentially more costly to construct several dams instead of one, such a system of dams could replace much of the energy generating capacity of LSS2, with potentially relatively insignificant energy losses from the flushing process and increased sediment outflows. The latter statement, however, ignores two critical issues that will be addressed next.

First, while flushing is taking place, no power is being produced because generators are taken offline. This will impact the reliability of power production. Performing flushing at LSS2-II and LSP2, compared to when no sediment management is performed, results in a loss in reliability for every level of power production, especially firm power. Reliability impacts will be assessed in the future as more information becomes available about the role these reservoirs play in the energy grid. Second, Figure 4.6 focuses on short-term energy production, whereas the positive impacts of sediment management become more visible in the long term, as sediment accumulation progressively impacts operations at dams where sediment (and therefore the reservoir's storage capacity) is not sustainably managed.

The sediment management alternatives for Sambor Dam offer a similar set of tradeoffs between sediment passage and hydropower production. That is, the alternative Sambor Dam is smaller, which improves sediment passage and makes flushing feasible. However, the smaller installed capacity and flushing process reduce energy production. The reduced reservoir storage means the alternative Sambor reservoir has an average trapping efficiency of 32% compared to the currently proposed Sambor (50%). This reduction translates into a large increase in sediment load passage, given the location of Sambor at the lower end of the river basin. In an unregulated system (about 160 Mt/yr inflow), this 18% reduction in trapping efficiency would result in a sediment discharge increase of about 29 Mt/yr, whereas in the system regulated to the extent of the MRC definite future scenario (80 Mt/yr inflow), the increase is about 14.5 Mt/yr. As with the LSS2 alternative discussed previously, the Sambor alternative has the additional advantage that sediment flushing is feasible. The associated increases in sediment passage depend on the frequency with which flushing is conducted. Additionally, the different location of the Sambor alternative compared to the currently proposed location creates the possibility of a natural sediment bypass. The potential impacts of both flushing and the sediment bypass are demonstrated in Figure 4.7. This figure shows the mean monthly sediment loads flowing into and discharged from the proposed and alternative Sambor Dam configurations.

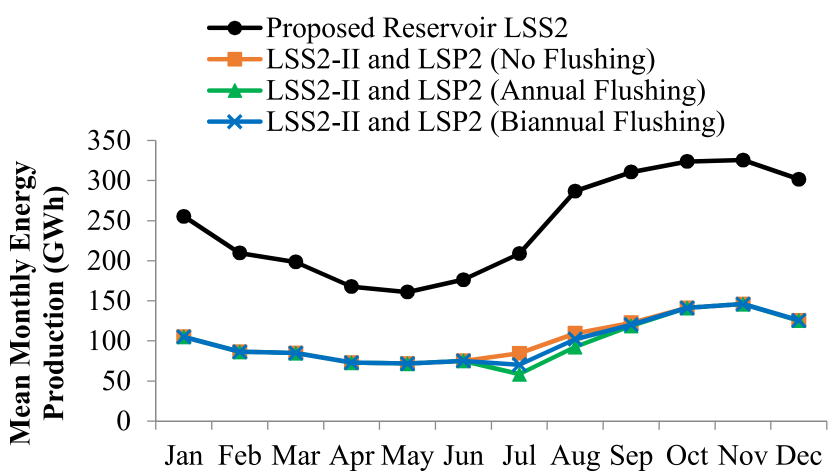


Figure 4.6: Simulated mean monthly hydropower energy production in Gigawatt hours (GWh) associated with the currently proposed Lower Se San 2 (LSS2) Dam and two alternative dams, Lower Se San 2-II (LSS2-II) and Lower Sre Pok 2 (LSP2), with flushing implemented.

If Sambor Dam is constructed as planned, much of its storage capacity could be lost due to sedimentation during the operating lifetime of the dam. The approximately 50% trapping efficiency of the planned dam suggests an annual sedimentation of 40 Mt, which is more than 33 million m^3 of sediment per year assuming an average bulk density of 1200 kg/m^3 for deposited sediment [*Xue et al.*, 2010]. In 50 years, almost 40% of the initial storage capacity could be lost to sedimentation. The storage capacity lost after 100 years will depend on how trapping efficiency declines at the site over time due to reduced storage capacity, but certainly more than 50% loss in initial storage capacity appears possible. Such a significant loss in storage capacity could potentially impact energy production and other dam functions, though the specific impacts will depend on the reservoir's specific operating policy, which is not known at this time. (Note that these assessments assume a consistent 80 Mt/yr mean annual influx of sediment. Declining sediment inflows due to construction of reservoirs throughout the LMB upstream could reduce sedimentation impacts at Sambor). Clearly, constructing a smaller reservoir with flushing and bypassing capabilities may be ecologically and operationally beneficial.

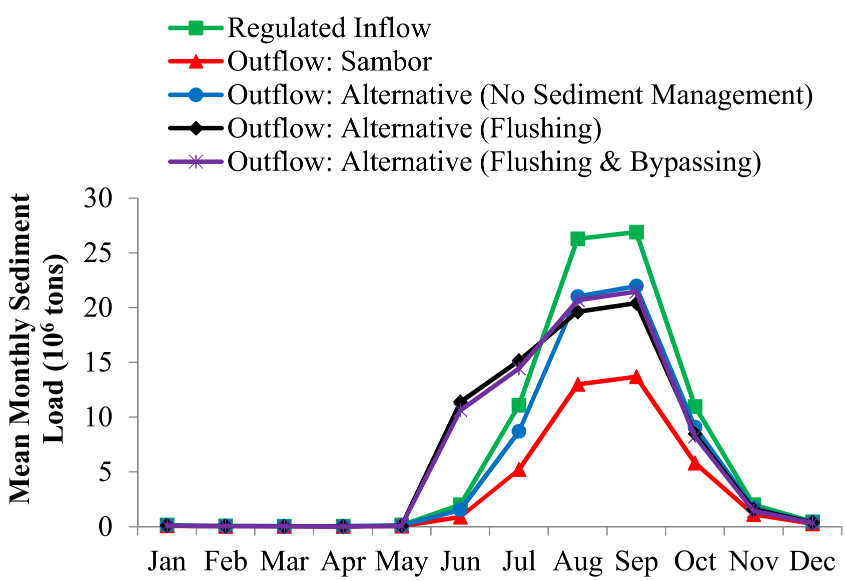


Figure 4.7: Mean monthly sediment load (10^6 tons) inflows and outflows at Sambor Dam site. All outflow time series result from the regulated inflow time series. This demonstrates the simulated potential for the Sambor alternative reservoir proposed here, combined with flushing and sediment bypassing, to improve sediment passage compared to current plans. The case in which bypassing is conducted without flushing is not shown, as sediment outflows were not significantly different from the outflows corresponding to no sediment management.

Simulation results indicate that implementing annual or biannual flushing at the site would increase sediment discharge by about 19% compared to the case in which no sediment management is implemented at the same alternative dam (77.3 Mt/yr instead of 64.7 Mt/yr). As was the case with LSS2 flushing alternatives, the increased sediment discharge during flushing is produced on average early in the wet season (or late in the dry season). Once again this may have important ecological implications.

Surprisingly, conducting sediment bypassing does not produce any increase in mean monthly sediment discharge compared to the case in which no sediment management is implemented at the same alternative dam. This does not mean that the sediment bypass does not work. In fact, the sediment bypass effectively diverts about 28% of the inflowing sediment around the reservoir, resulting in reduced sediment inflows to the reservoir. However, the sediment bypass diverts large quantities of water around the reservoir during the flood season. This in turn increases the residence time of water and sediment in the reservoir during this period, thereby increasing the trapping efficiency from what it would otherwise be. Thus, the benefit of diverting 21.8 Mt/yr of sediment around the reservoir is offset by the increased trapping efficiency for the 72% of sediment that is not bypassed.

The relative improvement in sediment discharge that is possible with the sediment bypass depends on the trapping efficiency of the reservoir. For example, results from other simulations (not discussed here) demonstrate that if the trapping efficiency of the reservoir without sediment management is 45% instead of 32%, the bypass would instead produce an increase in sediment load discharge of 22% compared to the reservoir without sediment management implemented. When both flushing and bypassing are implemented at the same time, there is only a very slight improvement in sediment discharge (0.25 Mt/yr) compared to the case in which the reservoir is only flushed (and no bypass exists).

To further explore this result regarding the bypass, future work should include sensitivity analysis that explicitly accounts for the impact of the following factors on the relative effectiveness of the sediment bypass: (1) the fraction of the suspended sediment load that is distributed into the bypassed flow versus into the reservoir; and (2) trapping efficiency, which affects the incremental sediment benefit bypassing offers when both flushing and bypassing are conducted. Regarding the former factor, if the bypass diversion structure is constructed such that much of the suspended load in the water column can be distributed into the bypassed flow, the bypass could be much more effective than is reported here. Regardless of its potential influence on the sediment balance at Sambor, the sediment bypass option is important to consider because it offers a natural fish passage system; would inundate less surface area; and would likely be much more effective than flushing at preventing accumulation of bedload in the reservoir.

Just as with LSS2, the Sambor Dam alternative produces two primary impacts to power production: a loss in energy production due to reduced installed capacity, and a loss in energy production associated with the requirement that generators be taken offline during flushing. The results are not shown here because they are similar in appearance to the LSS2 energy impacts shown in Fig. 6. The reduced size of the Sambor Dam alternative results in about a 35% loss in annual energy production, mostly due to reduced installed capacity. Conversely, annual flushing further reduces annual energy production by only about 2%. Regarding the bypass, aside from the potential sediment and fish passage benefits, an additional advantage is that hydropower production can proceed normally during the bypassing process every year. This is because the installed turbine flow capacity at the currently proposed dam (and the Sambor alternative discussed here) is only twice the mean annual inflow rate (27,600 m^3/s). During the monsoon season the sediment bypass only diverts the portion of reservoir inflow that exceeds twice the mean annual inflow rate, so water that is diverted during bypassing would not have produced hydropower anyway.

5 Uncertainty Issues

The results presented in this paper rely on a variety of assumptions regarding the values of uncertain model parameters, for both the proposed dams (LSS2 and Sambor) and the multitude of dams that are proposed to be constructed upstream of them. The largest sources of uncertainty in the results presented here are related to inaccurate estimates of (1) sediment production and (2) sediment trapping efficiency. Regarding sediment production, the quantity of sediment produced in the Mekong basin is currently uncertain. Particularly in the 3S basins and on the mainstream Mekong River near Sambor, more frequent and spatially distributed sediment sampling, including grain size distributions and bedload estimates, are necessary to prepare more certain estimate of sediment production. Grain size distribution data will also enable improved estimates of reservoir sediment trapping efficiency, as will sedimentation records from existing reservoir sites. Both can be used to calibrate modeling assumptions regarding trapping efficiency.

Ultimately, both the quantity of sediment produced and the trapping efficiency of that sediment load (not just at LSS2 and Sambor, but at upstream reservoirs) will determine the quantity of sediment that is trapped. This controls (1) the potential impact that neglecting to conduct sediment management has on storage capacity and long-term energy production, and (2) the magnitude of sediment that could be released when flushing is conducted. Additional data, such as reservoir operating policies and improved total storage estimates, will enable improved predictions of sediment trapping and an improved understanding of the roles particular reservoirs (e.g., LSS2 and Sambor) play in the energy grids they serve. In the absence of the data outlined above, future work should include sensitivity analysis that explicitly varies assumptions regarding sediment production, sediment trapping efficiency (based on sediment size), and reservoir operating policies to capture the range of potential tradeoffs between sediment regime restoration and energy production.

6 Conclusions

Water resources infrastructure in the Mekong River Basin is growing at a rapid pace. This infrastructure will impact the natural flow and sediment regimes that in turn can impact the natural ecosystem of this biodiverse river and its basin. Sediment management opportunities should be considered for two reasons. First, it is important that lessons about successful implementation of sediment management practices be learned soon, so they can be applied throughout the basin to achieve sediment goals for the entire system. Second, retrofitting existing dams with sediment management facilities (e.g., low- and mid-level outlets) can be costly, so it is critical that dams be designed and constructed with sediment management goals in mind.

Our simulations suggest that as currently proposed, LSS2 Dam and Sambor Dam would trap large quantities of sediment, starving downstream ecosystems of this resource that transports nutrients and maintains the geomorphic makeup of the system, among other functions. Results of simulations also suggest that sediment management practices have the potential to reduce these adverse impacts. Reservoir re-location and resizing, along with frequent implementation of sediment flushing, could significantly increase sediment discharge compared to the current plans for LSS2 and Sambor. An additional opportunity at Sambor is a sediment bypass, the potential effectiveness of which appears promising but must be further evaluated. In addition to improved sediment passage (particularly for bedload), the Sambor alternative provides a natural fish passage channel. This could mitigate the potentially severe consequences (for the Mekong fishery) of building a dam on the Mekong River that would block major fish migration routes in the vicinity of critical ecosystems (Tonle Sap Lake and the Vietnam Delta).

While the management techniques evaluated here enable increased sediment passage, this benefit comes at a cost: diminished short-term energy production. Energy production is reduced for reservoirs at which sediment management is practiced, due to (1) the reduced reservoir size required to conduct sediment management, and (2) the flushing process itself that requires generators be taken offline. The majority of hydropower energy is lost because the smaller alternative reservoirs have smaller installed plant capacities, rather than due to the implementation of the sediment management practices (e.g., flushing and bypassing). This creates the possibility that numerous smaller dams could be constructed to replace the energy lost from one larger dam, particularly in the case of LSS2. The cost and long-term energy implications of this approach, as well as the potential increased difficulty of managing sediment in multiple dams, should be explored in future work. These lessons about tradeoffs are not limited to LSS2 and Sambor; rather, the findings discussed here have important implications for dams throughout the Mekong Basin, given the similarity in the monsoon-driven inflow and sediment conditions for various planned dams. Of course, the cost of sediment management with regard to hydropower losses will vary among sites, depending upon the objectives of different reservoirs, including the roles they serve in the energy grid.

Several issues highlighted in this paper should be investigated in future work. To begin, sensitivity analysis is required to better understand the effect of a variety of modeling assumptions on the results shown here. The effectiveness of different sediment management approaches, such as sediment bypassing, change depending upon various assumptions. The relative importance of these assumptions should be identified so data collection efforts can be prioritized. Next, the timing and magnitude of sediment released during flushing in the simulations described here are potentially inconsistent with the system's natural sediment regime, and could thus be harmful to the basin's ecosystems. Discussion in this paper has revolved around mean monthly and annual sediment loading released during flushing, whereas maximum daily sediment concentrations during flushing, and the duration of those concentrations, may be more important metrics for assessing potential impacts to the health of aquatic species and their habitats. These potential effects can be quantified with more detailed modeling and observation to assess the true potential of the techniques discussed here. Finally, assessment of the potential benefits of sediment management must account for the long-term benefits that are possible by maintaining a sustainable storage capacity. This study focused on short-term losses in hydropower production associated with sediment management, whereas the true benefit of flushing is more visible in the long term, when sedimentation will result in diminished functionality at reservoirs where sediment is not managed.

7 References

Annandale, G.W. (2012a), *A Climate Resilient Mekong: Sediment Pass-Through at Lower Se San 2*, Golder Assoc. Inc., Lakewood, CO, Nat. Heritage Inst., San Francisco, Calif.

Annandale, G.W. (2012b), *A Climate Resilient Mekong: Sediment Pass-Through at Sambor Dam*, Golder Assoc. Inc., Lakewood, CO, Nat. Heritage Inst., San Francisco, Calif.

Annandale, G.W. (2013), *Quenching the Thirst: Sustainable Water Supply and Climate Change,* CreateSpace, North Charleston, South Carolina.

Atkinson, E. (1996), *The Feasibility of Flushing Sediment from Reservoirs,* TDR Project R5839, Rep OD 137, HR Wallingford.

Baran, E., and C. Myschowoda (2009), Dams and fisheries in the Mekong Basin, *Aquatic Ecosystem Health and Management*, 12(3): 227-234.

Baran, E., and J. Nasielski (2011), *Reservoir Sediment Flushing and Fish Resources*, Report submitted by WorldFish Center, Phnom Penh, Cambodia to Natural Heritage Institute, San Francisco, CA, December 2011.

Baran, E. (2012), *Effects of Changes in Sediments and Nutrients on Biological Resources of the Lower Mekong*, Paper presented at "A Climate Resilient Mekong: Maintaining the Flows that Nourish Life", Natural Heritage Institute Workshop with the Ministry of Industry, Mines and Energy, Kingdom of Cambodia, on Options for Improving Sediment Passage at Dams, Phnom Penh, Cambodia, 14-15 February 2013.

Baran, E., S. Samadee, T.S. Jiau, and T.T. Cong, (2013), *Fish and fisheries in the Sekong, Sesan and Srepok basins (3S Rivers, Mekong Watershed), with special reference to the Sesan River*, Water and Food Challenge Program in the Mekong, Optimizing the management of a cascade of reservoirs at the catchment level, WorldFish Center, Phnom Penh, Cambodia.

Brandt, S.A. and J. Swenning (1999), Sedimentological and geomorphological effects of reservoir flushing: the Cachi reservoir, Costa Rica, 1996, *Geografiska Annaler* 81, 391-407.

Campbell, I.C., S. Say, and J. Beardall (2009), Tonle Sap Lake, The Heart of the Lower Mekong, in *The Mekong: Biophysical Environment of an International River Basin*, edited by I.C. Campbell, pp.251-267, Elsevier, Amsterdam.

Clift, P.D., D.L. Graham, and J. Blusztajn (2004), Marine sedimentary evidence for monsoon strengthening, Tibetan uplift and drainage evolution in East Asia, in *Continent and Ocean Interactions with East Asian Marginal Seas*, *Geophys. Monogr. Ser.* 149, pp. 259–282, AGU, Washington, D. C.

Dugan, P. (2008), Mainstream dams as barriers to fish migration: international learning and implications for the Mekong, *Catch and Culture*, 14(3): 9-15.

Fruchart, F. (2008), Why and how to flush a reservoir without environmental impacts, *Regional Workshop on Discharge and Sediment Monitoring and Geomorphological Tools for the Lower-Mekong Basin*, Vientiane, Lao PDR, 21-22 October 2008, 33.

Fu, K.D., and D.M. He (2007), Analysis and prediction of sediment trapping efficiencies of the reservoirs in the mainstream of the Lancang River, *Chinese Science Bulletin,* 52 (Supp. II) 134–140.

Hesse, L.W. and Newcomb, B.A. (1982), Effects of Flushing Spencer Hydro on Water Quality, Fish, and Insect Fauna in the Niobrara River, Nebraska, *North American Journal of Fisheries Management* 2, 45-52.

ICEM (2010), Hydrology and Sediment Baseline Assessment Working Paper, in *Baseline assessment report, Strategic Environmental Assessment of hydropower on the Mekong mainstream for the MRC*, ICEM (International Centre for Environmental Management), Hanoi, Vietnam.

Johnston, R., and M. Kummu (2012), Water Resource Models in the Mekong Basin: A Review, *Wat. Resour. Manage.*, 26, 429-455.

Junk, W. J., P.B. Bayley, and R.E. Sparks (1989), The flood pulse concept in river-floodplain systems, in *Proceedings of the International Large River Symposium (LARS), Can. Spec. Publ. Fish. Aquat. Sci.*, edited by D. P. Dodge, pp. 110–127.

Kondolf, G.M., C. Alford, and Z. Rubin (2011), *Cumulative Effects of Tributary Dams on the Sediment Loads and Channel Form in the Lower Mekong River: Progress Report through 30 September 2011*, Department of Landscape Architecture and Environmental Planning, University of California, Berkeley.

Kondolf G.M., Z. Rubin, C. Alford, J.T. Minear (2013), Cumulative sediment reduction to the lower Mekong River from planned dams, In Fukuoka S, Nakagawa H, Sumi T, Zhang H (eds), *Advances in River Sediment Research*, London, UK, Taylor and Francis.

Kummu, M., and O. Varis (2007), Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River, *Geomorphology*, 85, 275-293.

Kummu, M., X.X. Lu, J.J. Wang, and O. Varis (2010), Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong, *Geomorphology*, 119, 181–197.

Lamberts, D. (2006), The Tonle Sap Lake as a productive ecosystem, *Int. J. Water Resour. Dev.*, 22(3), 481-495.

Lu, X.X., and R.Y. Siew (2006), Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams, *Hydrol. Earth Syst. Sci.,* 10, 181–195.

Mahmood, K. (1987), Reservoir Sedimentation: Impact, Extent, Mitigation, *World Bank Tech. Rep. 71*, Washington, D.C.

Mekong River Commission (MRC) (2005), *Overview of the Hydrology of the Mekong Basin*, Mekong River Comm., Vientiane, November 2005, 73.

Mekong River Commission (MRC) (2010), *State of the Basin Report*, Mekong River Comm., Vientiane, 2010.

Mekong River Commission (MRC) (2011a), *Application of MRC Modelling Tools in the 3S basin*, Mekong River Comm., Vientiane, 2011.

Mekong River Commission (MRC) (2011b), *Basin Development Plan Programme Phase 2: Assessment of Basin-wide Development Scenarios*, Main Rep., Mekong River Comm., Vientiane, April 2011.

Mekong River Commission (MRC) (2012), Hydropower Project Database, Basin Development Plan Programme, Mekong River Comm., Vientiane, Lao PDR.

Meynell, P-J. (2011), *Mainstream Hydropower Dams in Cambodia and their Environmental Impacts*, Report to the Inland Fisheries Research and Development Institute (IFReDI).

Milliman, J.D., and R.H. Meade (1983), World-wide delivery of river sediment to the oceans, *Geology*, 91, 1-21.

Morehead, M.D., and J.P. Syvitski, E.W.H. Hutton, S.D. Peckham (2003), Modeling the temporal variability in the flux of sediment from ungaged river basins, *Global and Planetary Change*, 39(1-2): 95-110.

Morris, G.L., and J. Fan (1998), *Reservoir Sedimentation Handbook*, McGraw Hill, New York.

Newcombe C.P., and D.D. Macdonald (1991), Effects of suspended sediments on aquatic ecosystems, *North American Journal of Fisheries Management* 11 (1), 72-82.

Newcombe, C.P., and J.O.T. Jensen (1996), Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact, *North American Journal of Fisheries Management* 16 (4), 693-727.

Piman, T., T. Cochrane, M. Arias, A. Green, and N. Dat (2013), Assessment of Flow Changes from Hydropower Development and Operations in Sekong, Sesan and Srepok Rivers of the Mekong Basin, *Water Resour. Plann. Manage.*, 139(6), 723-732.

Power, M.E., W.E. Dietrich, and J.C. Finlay (1996), Dams and Downstream Aquatic Biodiversity: Potential Food Web Consequences of Hydrologic and Geomorphic Change, *Environ. Manage.,* 20(6), 887-895.

Sarkkula, J., J. Koponen, H. Lauri, and M. Virtanen (2010), *Mekong River Commission (MRC) Detailed Modelling Support (DMS) Project - Origin, fate and impacts of the Mekong sediments*, 53.

Sverdrup-Jensen, S. (2002), Fisheries in the Lower Mekong Basin: Status and Perspectives, *MRC Tech. Pap. 6*, Mekong River Comm., Phnom Penh, 103.

Vörösmarty, C.J., M. Meybeck, B. Fekete, K. Sharma, P. Green, and J.P.M. Syvitski (2003), Anthropogenic sediment retention: major global impact from registered river impoundments, *Global Planet. Change*, 39(1–2), 169–190.

Walling, D. (2005), Analysis and evaluation of sediment data from the Lower Mekong River. Report submitted to the Mekong River Commission, Dep. of Geogr., Univ. of Exeter.

Walling, D.E. (2008), The changing sediment load of the Mekong River, *Ambio,* 37(3), 150–157.

Walling, D.E. (2009), The Sediment Load of the Mekong River, in *The Mekong: Biophysical Environment of an International River Basin*, edited by I.C. Campbell, pp.113-142, Elsevier, Amsterdam.

Wang, J.J., X.X. Lu, and M. Kummu (2011), Sediment load estimates and variations in the Lower Mekong River, *Riv. Res. Appl.*, 27, 33-46.

White, W. R. (2001), *Evacuation of Sediments from Reservoirs*, Thomas Telford, London.

Wild T.B., and D.P. Loucks (2012a), Assessing the Potential Sediment-Related Impacts of Hydropower Development in the Mekong River Basin, *in Proceedings of the ASCE World Environmental and Water Resources Congress 2012*, pp. 2236-2246.

Wild, T.B., and D.P. Loucks (2012b), *SedSim Model: A Simulation Model for the Preliminary Screening of Sediment Transport and Management in River Basins, Version 3.0: Documentation and User's Manual*, Dep. of Civ. and Environ. Eng., Cornell Univ., Ithaca, New York.

Wild T.B., and Loucks, D.P. (2013), Managing Sediment in the Mekong River Basin: Tradeoffs Between Hydropower and the Environment, in *Proceedings of the ASCE World Environmental and Water Resources Congress 2013*, Cincinnati, OH, pp. 1297-1307.

Wild T.B., and D.P. Loucks (2014), Managing the Impacts of Reservoirs in the Mekong River Basin, *in Proceedings of the ASCE World Environmental and Water Resources Congress 2014*, Portland, OR, pp. 1070-1080.

Xue, Z., J.P. Liu, D. DeMaster, L.V. Nguyen, and T.K.O Ta (2010), Late Holocene Evolution of the Mekong Subaqueous Delta, Southern Vietnam, *Mar. Geol.*, 269, 45-60.

Ziv, G., E. Baran, I. Rodríguez-Iturbe, and S.A. Levin (2012), Trading-off Fish Biodiversity, Food Security and Hydropower in the Mekong River Basin, *Proceedings of the National Academy of Sciences* 109 (15): 5609-5614.

CHAPTER 5

CONCLUSIONS

1 Key Findings and Recommendations

Existing and planned reservoirs in the Mekong River Basin are poised to trap significant quantities of sediment and significantly alter the basin's natural sediment regime. Sediment trapped in reservoirs is unavailable to maintain the river's (and its tributaries') geomorphologic structure and support transport of nutrients to productive Mekong ecosystems, which host the second most biodiversity in the world. Chapter 2, Chapter 3 and Chapter 4 describe the development of a methodology to (1) identify reservoirs that could significantly alter the natural sediment regime, (2) assess alternative dam siting, design and operating policies that could improve sediment passage compared to current plans, and (3) quantify the losses in hydropower production that may be necessary to achieve improved sediment passage. This methodology is centered on the use of a daily flow-sediment simulation model, developed specifically for application in the Mekong Basin. The *SedSim* model is uniquely qualified for use in these studies because it can simulate a variety of specific reservoir sediment management strategies (e.g., flushing, sluicing, density current venting, bypassing and dredging) on the mass balances of sediment and water, as well as hydropower production, in large systems of rivers and reservoirs, within the limitations of existing data.

Chapter 2 describes application of this *SedSim* simulation model to evaluating the potential for reservoir sedimentation in the Se San, Sre Pok and Se Kong tributary basins (collectively called the "3S" basins) to the Mekong. Results of simulations described in Chapter

2 suggest that about 40%-80% of the suspended sediment load could be trapped in 3S basins reservoirs. (Sensitivity analysis shows that the actual extent of trapping will depend upon the number of reservoirs that will be located, designed and operated, and to a lesser extent the type and size of sediment produced). Chapter 2 identifies the Lower Se San 2 Dam in Cambodia as potentially severely impactful to the Mekong basin's sediment balance, with a theoretical trap efficiency as high as 79% at the confluence of the Se San Sre Pok Rivers, which control the discharge of 14.3 Mt/yr of sediment into the mainstream Mekong River. Chapter 3 identifies Sambor Dam in Cambodia as even more potentially impactful to the Mekong basin's sediment balance. Sambor Dam would be the southernmost dam in the basin, and with a theoretical trapping efficiency as high as 50%, would trap significant quantities of the river's total sediment load. Both dams are positioned in proximity to Cambodia's Tonle Sap Lake, the most productive inland freshwater fishery in the world, and the Vietnam Delta, which produces large quantities of rice and fish for consumption throughout Southeast Asia. These two ecosystems alone directly provide income and food security for tens of millions of people.

Given that the Mekong basin is still largely undeveloped, there still exist ample opportunities to build and operate dams in ways that reduce sediment trapping. Rather than focusing on predicting the various impacts of dams as currently designed, the studies presented in Chapters 3 and 4 assess alternative dam locations and designs (proposed by *Annandale* [2012a, 2012b]), as well as alternative reservoir operating policies, that could improve sediment passage compared to current plans. Results of simulations suggest that changes to siting, design and operations of dams can indeed significantly increase sediment discharge at planned dam sites. These alternatives may be of interest to the National governments of LMB countries because they increase sediment passage while still permitting hydropower production, though energy production is significantly reduced in some cases. Decision makers in LMB countries may wish to consider the following options for managing reservoir sedimentation at reservoirs, particularly those that are expected to be impactful, such as LSS2 and Sambor:

a) **Reducing reservoir size.** This reduces theoretical trapping efficiency; reduces the areal extent of sediment deposits, which become more difficult to remove when they become spread over large areas such as floodplains (e.g., LSS2 and Sambor); and enable various forms of sediment management that are not possible with large reservoirs (e.g., flushing, which requires the reservoir to be emptied).
b) **Changing reservoir location.** Relocating reservoirs to relatively narrower sections on the river is critical, as incised channels formed during methods such as flushing cannot access the sediment trapped in large floodplain areas.
c) **Installing low level outlets in the dam.** This permits a reservoir to be completely emptied and allows free flow through the reservoir for some desired duration. Dams should be designed with sediment management facilities in place, especially low- and mid-level outlets, as many sediment management techniques may become too difficult and expensive to retrofit (e.g., as would be required at most already constructed 3S basins dams in Vietnam).
d) **Implementing sediment management practices.** The methods explored here include flushing, routing and bypassing, which require changes to reservoir operating policies.

2 Barriers to Sediment Management

Several factors may limit the implementation of the particular sediment management techniques proposed here (namely flushing and routing) in practice, as described below.

2.1 *Reduced Energy Production*

First, to conduct sediment management, Chapters 3 and 4 demonstrate that a smaller reservoir is required, both to reduce trapping efficiency and enable sediment management (e.g., flushing). Such changes will reduce energy production in two primary ways: (1) the reduced head at the smaller replacement reservoir(s) will reduce the installed energy generating capacity of the hydropower plant, and (2) to a lesser extent, flushing and routing will reduce energy production during implementation these practices, as generators are offline when the reservoir is empty. These losses translate into direct losses in short-term hydropower production profits, which will reduce the likelihood that dam owners and operators have initial interest in sediment management. Note that other techniques, such as sediment bypassing, which could improve sediment passage at Sambor Dam, offer potential improvements in sediment passage without impacting energy production at all.

2.2 *Increased Initial Costs*

Implementing reservoir sediment management practices can require a variety of initial expenses, such as the installation of low and mid-level outlets in the dam, or other infrastructure (e.g., bypass structures). Additionally, Chapters 3 and 4 explore the possibility of replacing a single large dam with multiple smaller dams at which sediment can be more easily managed. This approach, too, could result in increased initial costs. Initial infrastructure costs may be much more manageable if sediment management facilities are included in the dam when it is constructed, rather than retrofitting such facilities into dams that have already been built [*Palmieri et al.*, 2003]. Most dams in the Mekong basin thus far have been constructed without sediment management facilities in place.

2.3 Lack of Significant Reduction in Long Term Storage Capacity

Theoretically, frequently implemented sediment management should increase the long-term storage capacity of a reservoir compared to one at which sediment management is not practiced. This suggests that if increased long-term storage capacity translates into increased long-term energy production, the costs associated with sediment management (described above) could potentially be offset by increased long-term energy production profits at those sites. (This, of course, does not consider the added costs of sediment management infrastructure, or the cost to construct several dams to replace one, as is proposed in Chapter 3 and Chapter 4 for LSS2). However, results presented in Chapter 3 and Chapter 4 suggest that for many potentially impactful proposed reservoirs, such as LSS2, sediment management-based gains in reservoir storage capacity may not translate into significant gains in energy production on an economically or politically relevant time scale. For example, in the 3S basins, simulated 100-year storage capacity losses from sedimentation exceed 20% in only five reservoirs in the full development scenario. Simply stated, the combined suite of planned reservoirs have significant capacity to store sediment (50 billion m^3 in the 3S basins) without many reservoirs individually losing an operationally critical fraction of their total storage capacity. At least for run-of-river reservoirs, a 20% loss in storage capacity over 100 years is not likely to impact energy production, thereby reducing the value added by installing costly sediment management infrastructure. (Without detailed dam specifications, reservoir operating policies, and information about the role dams serve in the energy grid, it is very difficult to make additional generalizations about the point at which 3S basins dams' functionality and profitability are significantly compromised by sedimentation).

2.4 Myopic Political and Economic Objectives

To understand the likelihood that sediment management measures ultimately take place, it is important to clarify who benefits from dams being constructed and when, as well as who has decision making authority. For many planned dams, the national governments of LMB countries (particularly in Lao PDR and Cambodia) are entering into agreements with foreign investors that build, own, and operate the dams for concession periods of up to 40 years, after which the investors transfer the dam to the national government (BOOT agreements). Simulation results in Chapters 2, 3 and 4 in the 3S basins (and for Sambor Dam) demonstrate that sedimentation is not likely to have an impact on storage capacity and operations (and therefore profits) on such a short time scale at many of the large dams with the highest theoretical trapping efficiencies or trapping potential. The short-term owners and operators will likely have no interest in investing in sediment management infrastructure, as well as incurring costs to change the siting, design and operating policies of dams, if there will be no return on this investment during the concession period. In such circumstances, it is the eventual owners and operators (the national governments of Lao PDR and Cambodia) that may be persuaded to conduct sediment management, because they are more likely to make management decisions that reflect the long term interests of their respective countries. The national governments also have the authority to require that new dams be constructed with sediment management facilities in place.

For decision makers in the national governments of LMB countries to view sediment management as an economic benefit, the traditional paradigm of economic analysis must be modified in at least two ways. First, the benefits of sediment management must include environmental benefits, especially those related to the valuable Mekong fishery. This alone is likely enough to suggest sediment management is economically beneficial, given the multi-billion dollar annual valuation of the Mekong fishery, and its importance to food security [*MRC*, 2010]. Second, the costs and horizon of the economic analysis must account for the fact that sedimentation can result in significant costs to recover silted out reservoir sites for use by future generations [*Morris and Fan*, 1998; *Palmieri et al.*, 2003; *Annandale*, 2013]. Setting economics aside, from a sustainability standpoint, decision makers may also need to grapple with the relative importance of intergenerational equity, as inaction may result in enormous costs being imposed on future generations to decommission dams and somehow manage the accumulated sediments.

Without any sediment management, eventually 3S basins dams will fill with large quantities of sediment during their useful lifetimes. These dams can either be left in place, possibly representing a safety hazard, or can be removed. If the defunct dam is left in place, the economic and political costs associated with potential failure are substantial, and future generations are denied the opportunity to benefit from a viable reservoir site, of which there are a limited number. On the other hand, removal of the dam may prove to be prohibitively costly in the absence of a retirement fund established by the original dam owners [*Palmieri et al.*, 2003]. Furthermore, to restore the viability of the reservoir site for future use in an environmentally conscious manner may require extremely costly management of the immense quantity of sediment deposited at the site [*Morris and Fan*, 1998]. In the 3S basins, 100 years of sedimentation would represent at least 1 billion m^3 of sediment to be managed by future generations. The absence of sediment management, or a retirement fund for future sediment management, is unequivocally unsustainable because it neglects the importance of intergenerational equity [*Annandale*, 2013].

2.5 Difficulty of Coordinated Implementation in Transboundary Multiple Reservoir Systems

Even if decision makers in the national governments of LMB riparian countries do decide that sediment management is important and economically viable at various reservoir sites, it may be particularly difficult to implement in practice. If multiple reservoirs become involved in sediment management (e.g., considering that 41 reservoirs are expected to be built in the 3S basins alone), it will become a significant operational and political challenge to coordinate the efficient release of sediment through cascade of reservoirs, particularly on the transboundary (Cambodia and Vietnam) Se San and Sre Pok Rivers. Otherwise, sediment releases from upstream reservoirs will simply be trapped in downstream reservoirs. Lessons about how to implement this in practice in an international river basin can be learned from France, where flushing at the Genissiat Dam is coordinated with operations at the Verbois and Chancy-Pougny Dams in Switzerland [*Fruchart*, 2008]. In Japan, reservoir operations are also coordinated for purposes of Sediment management, such as at Unazuki and Dashidaira Dams [*Kantoush et al.*, 2011]. If success is achieved in the Mekong, the lessons learned would benefit not only the Mekong basin, but other sediment-laden river basins that may face similar challenges in the future.

2.6 Environmental Concerns

Particular forms of sediment management, namely flushing, can alter the timing and magnitude of sediment released from the reservoir site compared to the natural conditions to which local aquatic ecosystems have adapted. As discussed in Chapters 3 and 4, careful attention must be paid to managing the concentration and duration of sediment releases downstream in an environmentally friendly manner, to be sure the diversity of aquatic plant and animal species downstream are capable of withstanding the new sediment regime. In contrast to flushing, sediment routing appears to offer the opportunity to discharge more sediment and in a way that more closely resembles the river's natural sediment regime, but significant energy losses are likely to occur. More frequent flushing or routing, from the very start of reservoir operations, would create the least environmental impact compared to less frequent management scenarios.

3 Limitations of Findings

There are several important limitations to the findings presented here. First, the methodology introduced in Chapter 2, including the *SedSim* model, are appropriate for planning-level studies, such as those described in this dissertation. As discussed in the next section of this chapter, more detailed assessments of the sediment management options presented here are possible with (1) more detailed models; and (2) more detailed data sets to drive those models, many of which are not currently available.

Second, regarding Chapter 3, while the concept of taking a large dam such as LSS2 and breaking it into several smaller dams [*Annandale*, 2012a] is technically feasible, the economic feasibility of this option must be evaluated, as constructing several dams to replace one dam could require costly infrastructure, not to mention that it can create additional fish passage challenges. Indeed, the economic feasibility of all forms of sediment management explored here, including at Sambor Dam, should be further explored.

Third, the observations and suggestions in this paper regarding reservoir operations to achieve flushing are most likely to be applicable to reservoirs and locations that share characteristics in common with the LSS2 site. For example, flushing and routing are likely to achieve the most success when conducted at locations that experience predictable annual wet and dry seasons, and that are on relatively narrow stretches of a river. Additionally, these techniques are more likely to be successful at smaller reservoirs that can be quickly emptied, and that have low- and mid-level outlets available. Impacts on energy production will be minimized at reservoirs that supply energy to an integrated regional energy grid that can compensate for permanent and temporary losses in energy production, and environmental impacts are likely to minimized at locations where downstream aquatic ecosystems are relatively well adapted to periods of high sediment discharge.

4 Future Work

Several issues highlighted in this paper should be investigated in future work. First, future work should include further evaluation of the methods and alternatives proposed here, particularly with more detailed sediment transport models. More detailed models will require more detailed data. Such detailed studies will need to focus on simulating effects at particular dams, rather than on consideration of large systems of dams, as is possible with a planning-level system simulation tool such as *SedSim*. Such studies should be capable of providing more accurate estimates of sediment concentrations released during flushing, particularly on a sub-daily basis, to evaluate potential impacts on ecosystems downstream. Additional data required to conduct such studies include spatially distributed sediment sampling in the 3S basins (including grain size distributions and bedload estimates), which would improve estimates of sediment production and trapping. Also, detailed reservoir operating policies, improved total storage estimates, and sedimentation records at existing sites would enable improved prediction of both sediment trapping and impacts on storage capacity and reservoir operations.

Second, as has been discussed, the economic feasibility of sediment management at potentially impactful sites must be assessed, including mechanisms to distribute the associated costs among investors, power customers, and those dependent on the productive Mekong fisheries. Third, future work must include better understanding the interactions among sediment, nutrients and aquatic species in the Mekong basin. Until these interactions are better understood, it is difficult to estimate the true economic and ecological benefit of sediment management.

5 References

Annandale, G.W. (2012a), *A Climate Resilient Mekong: Sediment Pass-Through at Lower Se San 2*, Golder Assoc. Inc., Lakewood, CO, Nat. Heritage Inst., San Francisco, Calif.

Annandale, G.W. (2012b), *A Climate Resilient Mekong: Sediment Pass-Through at Sambor Dam*, Golder Assoc. Inc., Lakewood, CO, Nat. Heritage Inst., San Francisco, Calif.

Annandale, G.W. (2013), *Quenching the Thirst: Sustainable Water Supply and Climate Change,* CreateSpace, North Charleston, S. C.

Fruchart, F. (2008), Why and how to flush a reservoir without environmental impacts, *Regional Workshop on Discharge and Sediment Monitoring and Geomorphological Tools for the Lower-Mekong Basin*, Vientiane, Lao PDR, 21-22 October 2008, 33.

Kantoush, S.A., T. Sumi, and Y. Takemon (2011), Lighten the load, *International Water Power and Dam Construction*, 38-45.

Mekong River Commission (MRC) (2010), *State of the Basin Report*, Mekong River Comm., Vientiane, 2010.

Morris, G.L., and J. Fan (1998), *Reservoir Sedimentation Handbook*, McGraw Hill, New York.

Palmieri A., F. Shah, G.W. Annandale, and A. Dinar (2003), *Reservoir Conservation Volume I: the RESCON Approach*, economic and engineering evaluation of alternative strategies for managing sedimentation in storage reservoirs, A contribution to promote conservation of water storage assets worldwide, Int. Bank for Reconstruction and Dev./The World Bank, Washington, D.C., 101.

APPENDIX:

SEDSIM MODEL DOCUMENTATION AND USER MANUAL

Sediment Simulation Screening (*SedSim*) Model

A Simulation Model for the Preliminary Screening of Sediment Transport and Management in River Basins (Version 3.0)

Documentation and User's Manual

Matilija Dam Restoration Project (California, USA).[7]

Thomas B. Wild and Daniel P. Loucks (2013). *SedSim* Model: A Simulation Model for the Preliminary Screening of Sediment Transport and Management in River Basins, Version 3.0: Documentation and User's Manual. Department of Civil and Environmental Engineering, Cornell University, Ithaca, NY USA. October.

[7] Photo taken from U.S. Bureau of Reclamation website at: http://www.usbr.gov/pmts/sediment/projects/Matilija/MatilijaDam.html

1 Model Overview

This documentation describes the *Sediment Simulation Screening Model (SedSim)*, a simulation model for the preliminary screening of sediment transport and management in River Basins. The *SedSim* model was developed at Cornell University, in partnership with the Natural Heritage Institute (NHI). The *SedSim* model is a sediment accounting tool that was originally developed for use in the Mekong River basin. This model performs a daily time-step mass-balance simulation of flow and sediment that is intended to predict in relative terms the spatial and temporal accumulation and depletion of sediment in river reaches and in reservoirs under different reservoir operating and sediment management policies. Thus, the model is expected to be used for estimating sediment transport in river basis including those that have experienced (or will experience) extensive reservoir development. The *SedSim* model runs in Microsoft Excel. The source code is written in the Visual Basic for Applications (VBA) language. The model consists of three spreadsheets, the main model interface and the input and output files.

2 Model Background and Development

Background: Flow and Sediment in the Mekong River Basin

First, a brief review of background regarding the flow of water and sediment in the Mekong River Basin will be useful, as *SedSim* was developed for use in the Mekong Basin and thus employs assumptions appropriate for this region. The Mekong River is among the world's largest rivers in terms of length and sediment load. It delivers approximately 160 million metric tons of sediment and 460 km^3 of fresh water per year into the South China Sea [*Milliman and Meade*, 1983]. Originating from the Tibetan Plateau, the 4750 km long Mekong River runs through China (in the Yunnan province where it is called the *Lancang Jiang*), Myanmar, Thailand, Lao PDR, Cambodia and Vietnam before entering the South China Sea The river's watershed (Fig. 2.1) covers about 800 thousand km^2. Table 1 details the flow and catchment area contributions of the six Mekong River Basin countries [*Mekong River Commission (MRC)*, 2005].

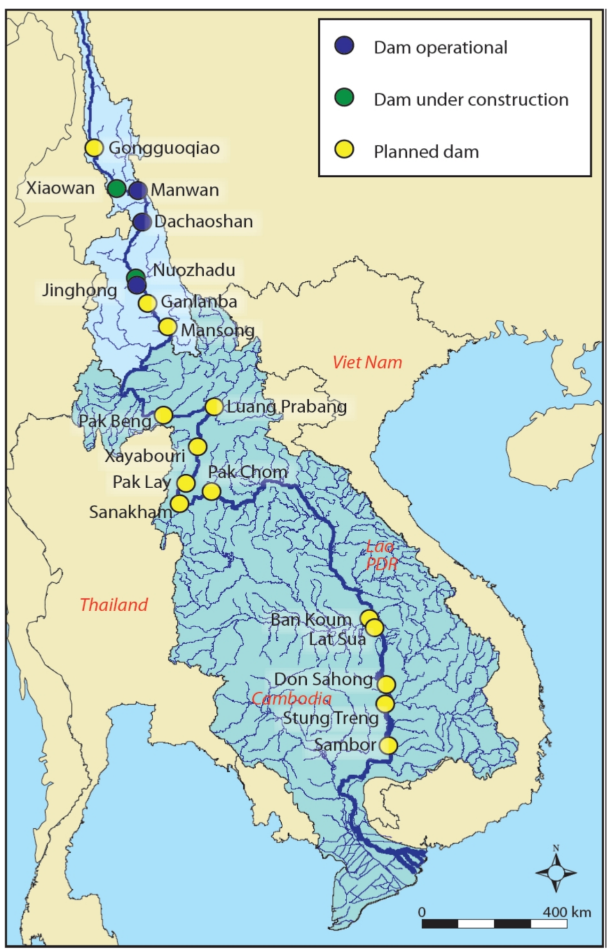


Figure A2.1. The Mekong River Basin showing present and potential main stem reservoirs.[8]

[8] Figure taken from *MRC* [2009].

Table 2.1. Flow and catchment area information for the six Mekong River Basin countries [*MRC*, 2005].

	China	Burma	Lao PDR	Thailand	Cambodia	Viet Nam	Total
Area (10^3 km^2)	165	24	202	184	155	65	**795**
Catchment (%)	21	3	25	23	20	8	**100**
Flow (%)	16	2	35	18	18	11	**100**

The climate of the Mekong Basin is controlled by the Monsoon, which produces wet and dry seasons of approximately equal length [*MRC*, 2005]. The Southwest monsoon produces the wet season that is responsible for the majority of the basin's annual flow and generally lasts from May until late September (or early October). Tropical cyclones can occur throughout the basin during the wet season, and generally occur during the end of the wet season. The Northeast Monsoon produces the dry season by shifting cooler temperatures from China into the basin. The dry season generally lasts from late October until April.

The Mekong River and its tributaries form a unique hydro-ecological system that not only supports one of the world's most diverse riverine ecosystems (containing over 560 endemic fish species and over 300 globally threatened vertebrate species), but also provides food security for more than fifty million people in the Indo-Burma region. This delicate ecosystem will likely be impacted by the planned development of hydropower reservoirs along the main stem and its tributaries [*MRC* (2010)].

Throughout the Mekong Basin, there is a lack of consistently collected, high quality sediment data [*Wang et al.*, 2011], which renders very difficult the development and calibration of sediment transport models for this region. For example, this is particularly true in the Sre Pok, Se San and Se Kong (collectively called the "3S") sub-basins, a map of which is provided in Figure A2.2. Sediment models must be adapted to the data available. The accuracy of the results of simulations with this sediment model is limited in part by the availability of sediment data. Existing data only permit the assumption of a generic sediment particle (different sediment types, grain sizes, etc. are not considered). Several researchers have estimated the annual suspended sediment load of the Mekong River to be approximately 160 million tons (Mt), with about half of this load generated in the Upper Mekong Basin (in China), and the other half generated in Lower Mekong Basin countries [*Walling*, 2005; *Gupta and Liew*, 2007]. The construction of dams in China on the upper Mekong called the Lancang River is expected to trap most of the 80 Mt generated in this region [*Kummu and Varis*, 2007]. Some researchers have investigated the basin-wide potential for reservoirs to trap sediment in the Lower Mekong Basin [*Kummu et al.*, 2010], but more detailed modeling is still needed to predict impacts in specific areas.

Reservoirs generally trap all of the inflowing river's bedload and some fraction of the inflowing suspended load. The extent of trapping depends on many factors, including the residence time; the reservoir's trap efficiency; the amount, texture and size of inflowing sediment; and the reservoir's operating policy [*Morris and Fan*, 1998]. Flowing water naturally transports sediment as a means of dissipating energy, so when a reservoir traps sediment and discharges the clear (or 'hungry') water downstream, that water has an increased capacity to scour and transport sediment

Figure A2.2. Se San, Sre Pok, and Se Kong (3S) tributary basins to the Mekong River, showing existing and proposed hydropower dams[9]. Based on data from *MRC* [2012].

[9] This figure is reproduced with permission from John Wiley and Sons: Wild, T.B., and Loucks, D.P. (2014), *Water Resour. Res.,* 50, 5141-5157, DOI: 10.1002/2014WR015457.

[*Kondolf*, 1997]. This can result in a variety of effects, including bed incision, armoring of the bed, bank failure due to undercutting, lowering of the groundwater table, and isolation of the river from its floodplain.

In the Mekong basin, sediment that is trapped in reservoirs is unable to support ecosystem health and productivity in sensitive downstream areas, which in the Mekong basin includes the Vietnam Delta; wetlands; the nearshore ocean ecosystem; and floodplains, the productivity of which depend on sediment for nutrient transport. Altered transport processes could also disrupt the maintenance of important physical features of Mekong fisheries. For example, an altered sediment regime could cause the filling in of deep pools.

***SedSim* Model Development**

SedSim is most useful when used in conjunction with other modeling tools. Figure A2.3 presents a conceptual diagram of the modeling tools that are suggested to be used in conjunction with *SedSim*. The Soil and Water Assessment Tool (*SWAT*), which was calibrated for the Mekong River Basin by the Mekong River Commission, may be used to generate local watershed flows (or incremental flows). Within *SedSim*, reaches, reservoirs and diversions are connected by Junction nodes. Runoff from the watershed, which is generated by *SWAT*, enters the *SedSim* model at select junction nodes, after which the water instantaneously enters the reach or reservoir that sits immediately downstream of the junction. The *SedSim* model conducts reservoir operations and reach routing procedures, and tracks the accumulation and depletion of sediment in reservoirs and reaches, independently of the other models (e.g., SWAT and RESCON). The *RESCON* model, which is referenced in Figure A2.3 but discussed in more detail later in the *Sediment Management* section of this chapter, is a tool that aids in assessing the feasibility of applying particular reservoir sediment management techniques at particular reservoir sites [*Palmieri et al.*, 2003; *Kawashima et al.*, 2003]. While this figure references the specific models that have been used to conduct simulations in the Mekong basin (i.e., SWAT and RESCON), other models performing similar functions can just as easily be used instead.

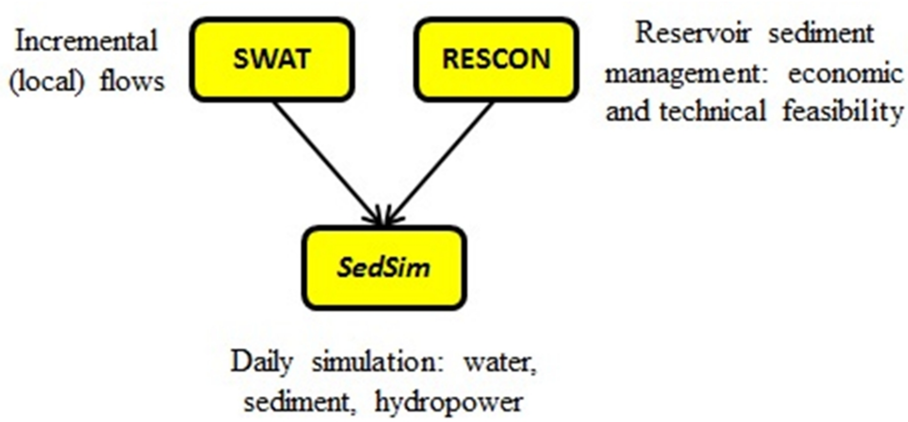


Figure A2.3. An example of the suggested *SedSim* modeling structure, including other modeling tools suggested to be used in conjunction with *SedSim*.

Chapter 11 offers a detailed description of the *SedSim* approach to water and sediment transport and storage in reaches and reservoirs.

To estimate hydropower production and release capacity of reservoir outlets, the model requires that Elevation-Volume-Area information be provided for each reservoir, so the model can determine the elevation (mamsl) corresponding to the storage volume (m^3) at the beginning and end of every simulated day. The original Elevation-Volume-Area relationship provided by the user is modified over time as either (1) sedimentation reduces the water volume and surface area at each water surface elevation, or (2) sediment management practices increases the water volume available at each water surface elevation.

For each reservoir, the *SedSim* model requires the user to select a reservoir type from four different options, shown in Figure A2.4. A reservoir can either have, or not have, the capability to produce hydropower. Within the two hydropower categories, a reservoir can either only have the capability to release water downstream, or can have the added capability to divert water to another location in addition to downstream. At diversion reservoirs, all diverted water and sediment is immediately transferred to the specified location without routing (i.e., there is no routing time lag in the transfer of diverted water and sediment from one location to another).

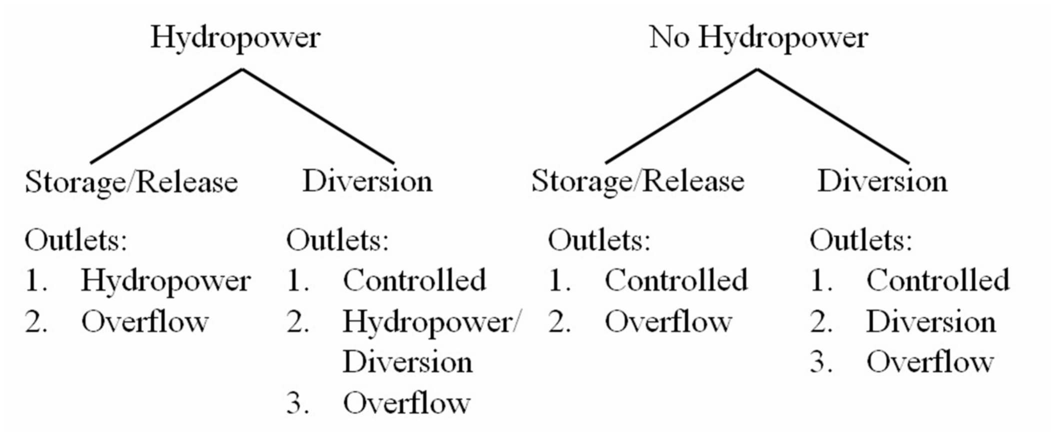


Figure A2.4. Diagram of the four different reservoir types a user can simulate using the *SedSim* model.

These reservoir type distinctions are important for the user to establish so the model can determine appropriate release outlets for each reservoir type, as well as the priority of releases from those outlets. The outlet types established for each reservoir type are listed in Figure A2.4, but each is described in more detail below. First, it will be important to discuss some important general points about specifying outlets in *SedSim*.

First, it is suggested that for each reservoir to be simulated, the user specify the same type of outlets listed in Figure A5 for the reservoir type being simulated, though this is not a requirement. For example, if a reservoir with no hydropower or diversion capabilities is to be simulated, a controlled and overflow outlet should be specified by the user. However, if the user only includes the overflow outlet (i.e., omits the controlled outlet), only the overflow outlet will be capable of releasing flow. If the user specified a hydropower outlet for this reservoir type, it would not be used, because this reservoir type is not capable of producing power.

When the user selects a reservoir type (in the "Reservoir Specifications" worksheet), the model must be supplied with information for each of its outlets. It is very important that the user have a maximum of only one outlet of each type that is appropriate for the reservoir selection (again, see Figure A2.4). For example, even if the reservoir in reality has 5 spillway gates, the individual capacities of these gates should be combined into one larger gate when reservoir data are provided by the user. Additionally, the maximum capacity of each outlet to release flow is dependent only on the water surface elevation in the reservoir. The user must establish the maximum discharge capacity of each outlet for elevations at which the capacity is different. Finally, all outlets are assumed to be controllable. For example, even if the water surface elevation in a reservoir is at the level of the spillway outlet, the spillway is not assumed to release any water unless the storage or elevation target for the reservoir dictates a release is needed. So, while possible it is not likely water will be stored above the spillway elevation since the target elevation or volume would not normally be set greater than this limit.

Note that the discussion below references specific sediment management techniques, detailed descriptions of which are presented later in this chapter.

Reservoir outlets include:

1. **Controlled Outlet.** This outlet type, which does not result in any hydropower generation, is used to ensure that water is released into the downstream channel. For example, diversion reservoirs can divert a significant volume of water away from the downstream channel, but this outlet is located at a low point in the reservoir to increase the likelihood that some water can be released downstream.

2. **Hydropower Outlet.** This outlet type directly supplies the turbines with flow to generate hydropower. Water released through this outlet type is discharged into the downstream channel after passing through the turbines. Importantly, the model does not limit discharge through the hydropower outlet when the provided capacity (MW) of the powerhouse is exceeded. That is, the user-supplied capacity vs. elevation curve for the hydropower outlet applies to the ability to supply water to the turbines, rather than a power production capacity-based discharge limit. The model does, however, prevent power production in excess of the user-provided maximum power production capacity of the plant. Any water being released through this outlet that does not generate hydropower is also classified as spilled flow in the model output.

3. **Diverted Outlet.** This outlet type, which does not result in any hydropower generation, diverts water away from reservoir's downstream channel. The location to which water is diverted can be within the basin being modeled, or outside of the modeled system.

4. **Hydropower/Diversion Outlet.** This outlet type directly supplies the turbines with flow to generate hydropower. This outlet type is only different from the hydropower outlet type described above in that the water is diverted away from the downstream channel after producing power.

5. **Spillway (overflow) Outlet.** This outlet type, which does not result in any hydropower generation, is a spillway. Thus, this outlet is assumed to be located at the top of the active storage zone, which is the zone of the reservoir that is operated for hydropower production. These outlets are used to drain any storage space above the active storage zone (i.e., the flood storage zone). Assuming the reservoir's storage or elevation targets are below the spillway outlet, any water stored above the spillway outlet is spilled into the downstream channel, assuming the outlet has the capacity to release the water.

6. **Low level Outlet.** This outlet type, which does not result in any hydropower generation, is used to release water and sediment into the downstream channel for sediment management purposes. This outlet type can be used to release water during flushing and density current venting. For flushing, the outlet should be properly sized to enable drawdown of the reservoir, as well as properly sized to release reservoir inflows during the flushing period. Additionally, if effective flushing is simulated, the invert elevation of this outlet should be close to the original river bed elevation at the reservoir site. (Important: The first elevation entry in the elevation-capacity table for this outlet will be assumed to be the original river bed elevation for flushing calculations). This outlet is the only operable outlet during flushing once the water levels drop below the operating levels of other outlets, due to the low water surface elevation maintained during flushing. For density current venting, the low level outlet should be sized to discharge the reservoir inflow at normal operating water surface elevation during inflow events that produce concentrations significant enough to warrant density current venting.

7. **Mid Level Outlet.** This outlet type, which does not result in any hydropower generation, is used to release water during sluicing (a form of sediment management that includes drawing the reservoir level down to the mid-level outlets and releasing the reservoir inflow, usually during high inflow season). The mid-level outlets are opened when all criteria are satisfied to initiate drawdown for sluicing, and are generally kept open throughout sluicing. The goal of sluicing is to release the reservoir inflow, so in the event that hydropower outlets exist and have the capacity to release the inflow during sluicing, the mid-level outlets would not be used.

All outlets are assumed to be functional regardless of the amount of sediment contained in the reservoir. That is, even if sedimentation significantly reduces a reservoir's water storage capacity, all of the outlets are assumed to remain functional for water release throughout simulation.

In addition to selecting a reservoir type, the user must define an operating policy for every reservoir (i.e., how much water to release every day in m^3/s). The model allows operating policies based on (1) storage volume targets or (2) storage elevation targets. Both options require that the user pre-establish a time series of targets. (Future versions of the model may allow release decisions in response to the reservoir's storage or elevation state, rather than pre-established targets).

Regardless of which target option is selected, the model implements a similar approach in operating each reservoir, which is to determine how much water must be released, if any, to meet the target, given the initial reservoir storage, potential evaporation, constraints on the release capacity of the reservoir's user-defined outlets (discussed above), and minimum environmental flow constraints. Once the model has determined how much water must be released during the simulation period to meet the specified target, discharge is distributed among the outlets using a set of priorities that depend on the reservoir type. For reservoirs that can only release water downstream (regardless of whether or not the reservoir produces hydropower), the primary outlet (controlled or hydropower) discharges as much of the target flow release as possible, and the overflow outlet only receives the remainder of flow that could not be distributed to other outlets due to release capacity constraints at those outlets. If drawdown flushing is being conducted, any flow that could not be released by other outlets is released by the low level outlet. For diversion reservoirs, which can divert water away from the downstream channel, the approach is only slightly different. In this case, water is first allocated to the controlled outlet (the primary outlet responsible for releasing water downstream) to meet any user-established minimum environmental flow constraints, after which the hydropower/diversion outlet, overflow outlet and low level flushing outlet are allocated flow (assuming they have capacity), in that order.

1. **Storage Targets.** If this option is selected, a water storage target (m^3) must be established for the end of each simulation day. This input must be provided in the form of a time series. If sediment accumulates in a reservoir and a "Storage Target" policy is selected, the model will only store the water required to meet the storage target, without regard to the impact of sediment on the elevation of the water. For example, if one specifies an operating policy that assigns an identical target value for the reservoir for the duration of simulation, the model will attempt to meet this target, but the water surface elevation to which the constant storage target corresponds will continue to rise as simulation proceeds. (The second reservoir operations option, presented below, offers an approach that accounts for this sediment accumulation issue).

2. **Elevation Targets.** If this option is selected, a water surface elevation target (m^3) must be established for the end of each simulation day. This input must be provided in the form of a time series. If sediment accumulation in the reservoir is negligible in comparison to the storage capacity, then this policy option will result in the same policy one would establish just using storage targets, because an elevation corresponding to every water storage value can be determined from the Elevation-Volume data. However, if sediment accumulation in the reservoir is significant, this option will allow specified elevations to be maintained in the reservoir over time, which may require that less water be maintained in storage as the simulation proceeds due to sediment accumulation in the reservoir's storage space.

Sediment Simulation

A number of studies have indicated a strong correlation between water flow and suspended sediment concentration (SSC) in both large and small, and gauged and ungauged rivers [*Milliman and Meade*, 1983; *Walling and Webb*, 1983; *Meybeck et al.*, 2003; *Morehead et al.*, 2003]. Factors such as relief and lithology may also play important roles in sediment production [*Vörösmarty et al.*, 2003]. In keeping with this commonly observed watershed characteristic, the *SedSim* model assumes that sediment can only enter the network of reaches and reservoirs at the same exact locations at which water flows enter. The rating curve, based on the power regression of *SSC*, C_s (kg/m^3), on discharge, Q (m^3/s), is given by

$$C_s = kQ^x \qquad (A2.1)$$

The relationship in Eq. (A2.1) is used for two purposes: (1) to generate daily incremental sediment loads at locations in the modeled system at which incremental flows are generated (by an external hydrologic model or other means); and (2) to generate sediment loads to be discharged from river reaches (channels), in keeping with the concept that each reach has a 'carrying capacity' to produce sediment as a function of reach discharge. The parameters 'k' and 'x' in Eq. (A2.1) will be referred to as 'c' and 'd', respectively, when discussing the application of this general equation to incremental sediment load generation (see Eq. (A2.2)). Conversely, the parameters 'k' and 'x' in Eq. (A2.1) will be referred to as “a” and “b”, respectively, when discussing the application of this general equation to sediment discharge from reaches (see Eq. (A2.3)).

As was discussed previously, most estimates of sediment loads in the lower Mekong basin predict that about 80 Mt/yr will be generated in the Lower Mekong Basin. *Kondolf et al.* [2011] partitioned this 80 Mt/yr of sediment among nine geomorphic regions, which were delineated based on climatic, geologic, topographic, and tectonic features. Sediment yields (t/km^2-yr) were determined by *Kondolf et al.* [2011] for each region. For example, the 3S basin lies within two geomorphic provinces: the Kon Tum Massif and the Tertiary Volcanic Plateau, which have estimated yields of 280 t/km^2-yr and 290 t/km^2-yr, respectively [*Kondolf et al.*, 2011]. While this annual sediment yield information is useful, the *SedSim* model is operated with a daily time step. Thus, daily sediment load inputs to junction inflow locations in the *SedSim* model are required. To accomplish this, sediment is generated on a daily basis with a version of Eq. (A2.2) that has been uniquely calibrated for each incremental input location. The model user must specify a d_i value. The user may wish to set the parameter ‘*d*’ so that proportionally more sediment is transported during higher discharge events, as is often observed in practice [*Walling*, 2009]. The model determines a c_i value for each incremental input location such that the mean annual sum of daily sediment loads generated in the unregulated system equals the product of the watershed area that contributes to the incremental flows and the annual sediment yield per unit area (described above) for the input location. In symbolic form, the generated yields will satisfy the following equality:

$$\frac{1}{N}\sum_{t=1}^{T} c_i \left(Q_i^{inc}(t)\right)^{d_i} Q_i^{inc}(t)\Delta t = A_i^{inc} Y_i^{inc} \text{ for all incremental inflow locations } i \qquad (A2.2)$$

$$c_i = \frac{A_i^{inc} Y_i^{inc}}{\frac{1}{N}\sum_{t=1}^{T}\left(Q_i^{inc}(t)\right)^{d_i+1}\Delta t}$$

where T is the simulation duration (in days), N is the average number of simulation years (=T/365), c_i is the parameter being calibrated for location i, d_i is a specified parameter for location *i*, $Q_i^{inc}(t)$ is the daily incremental flow at location *i*, *Δt* is the time step (number of seconds in simulation time step in one day), A_i^{inc} is the watershed area (km^2) that incrementally contributes to location *i*, and Y_i^{inc} is the average annual sediment yield (Mt/yr-km^2) per square *Km* of the incremental watershed.

Each Eq. (A2.2) is solved in Excel, assuming the user chooses to perform parameter calibration within the model. The model also offers two additional options: (1) specifying one set of two parameter values to be used for all incremental inflow locations, or (2) specifying a separate set of two parameter values for every incremental inflow location. Selecting one of these additional options requires that user determine appropriate values externally.

The model currently assumes that there are no limitations to the sediment supply from the watershed, in that sediment is continually generated as a function of flow without exhausting sediment supply. However, sediment availability in river reaches can be optionally limited. All sediment that exists within the modeled system, including sediment deposits that existed within the system prior to the start of simulation and the incremental loads that enter the system during simulation, are subject to several transport processes. These transport processes are different for reaches and reservoirs.

For reaches, during a one-day time period, any sediment entering a reach element can either settle (with the possibility of being eroded at a later time), or can be discharged from the reach as the model attempts to satisfy the sediment discharge from the reach generated based on an equation that is identical in form to Eq. (A2.1). To clarify, previously discussion of Eqs. (A2.1) and (A2.2) focused on incremental sediment loading. However, the *SedSim* model permits sediment to be generated from within the system as well. Thus, if no sediment incrementally entered the system from watershed runoff, quantities of sediment would be scoured from reaches to compensate for this input of sediment-deprived water. (Sediment can only be generated within the system in reaches, not in reservoirs. This assumption will be modified if the *SedSim* model is further improved to include treatment of flushing processes). The amount of sediment discharged from a given reach is also in the form of Eq. (A2.1), where once again the *a* value is calibrated given the *b*, but slightly differently than they were calibrated for the incremental flows. Again, the user may wish to set the parameter "b" so that proportionally more sediment is transported during higher discharge events, as is often observed in practice [*Walling*, 2009]. The reach sediment rating curve coefficients are calibrated for each reach such that the mean annual sum of daily sediment loads discharged from the reach in the unregulated system is equal to the sum of the mean annual sediment loads generated incrementally at all upstream incremental input locations. Note that while a regulated *SedSim* model consists of both reaches and reservoirs, the unregulated system consists only of reaches. Thus, the *a* value is determined for the locations in the network where reservoirs are sited, treating the unregulated reservoir site as a reach. In symbolic form, each *a* value is determined by the model to satisfy the following equality:

$$\frac{1}{N}\sum_{t=1}^{T} a_j\left(Q_j^{out}(t)\right)^{b_j} Q_j^{out}(t)\Delta t = \sum_{i\in U}\left(A_i^{inc}Y_i^{inc}\right) \text{ for all reaches } j \qquad \text{(A2.3)}$$

$$a_j = \frac{\sum_{i \in U} \left(A_i^{inc} Y_i^{inc} \right)}{\frac{1}{N} \sum_{t=1}^{T} \left(Q_j^{out}(t) \right)^{b_j+1} \Delta t}$$

where T is the simulation duration (in days), N is the average number of simulation years =(T/365), a_j and b_j are the parameters being calibrated for reach j, U is the group of all upstream incremental flow locations i that contribute to the outflow at the outlet of reach j, $Q_j^{out}(t)$ is the daily outflow from reach i, Δt is the time step (one day), A_i^{inc} is the watershed area (km^2) that incrementally contributes to location i, and Y_i^{inc} is the average annual sediment yield (Mt/yr-km^2) for the incremental watershed area.

Each Eq. (A2.3) is solved in Excel, assuming the user chooses to perform parameter calibration within the model. The model also offers two additional options: (1) specifying one set of two parameter values to be used for all reach sediment rating curves, or (2) specifying a separate set of two parameter values for every reach sediment rating curve. Selecting one of these additional options requires that user determine appropriate values externally.

These same parameters a_j and b_j for each reach j in the unregulated system are then stored in the model and are used to determine flow-based sediment discharge from each reach in the regulated system. Thus, Eq. (A2.3) assumes that the 3S basin is in relative balance in its unregulated state, exporting approximately what is eroded on an average annual basis. However, because the unregulated system coefficients a_j and b_j are maintained for the reaches in the regulated system, alterations of reach flow rates by reservoirs and reduction of sediment availability due to reservoir sediment deposition can both result in significantly altered sediment discharge characteristics as given by Eq. (A2.3).

The sediment concentration entering a reservoir is diminished due to the trapping or settling of sediment in the reduced flow behind the dam. Some fraction of the sediment entering a reservoir is trapped. Sediment that has previously settled in a reservoir can only be removed by simulating a sediment management practice, such as flushing. The trapped fraction, *TE(t,r)*, for each reservoir *r* in each day *t* is determined using the *Brune* [1953] method, which is depicted in Figure A2.5. The *Brune* [1953] method uses data from reservoirs in the United States to predict trapping efficiency as a function of the reservoir's residence time (or Capacity:Inflow ratio). Residence time for each simulation day is determined in *SedSim* using the average total water storage in the reservoir divided by the outflow or release of water from the reservoir. *SedSim* will compute trapping efficiency based on either a running monthly or annual average of residence time, as specified by the user in the input data file.

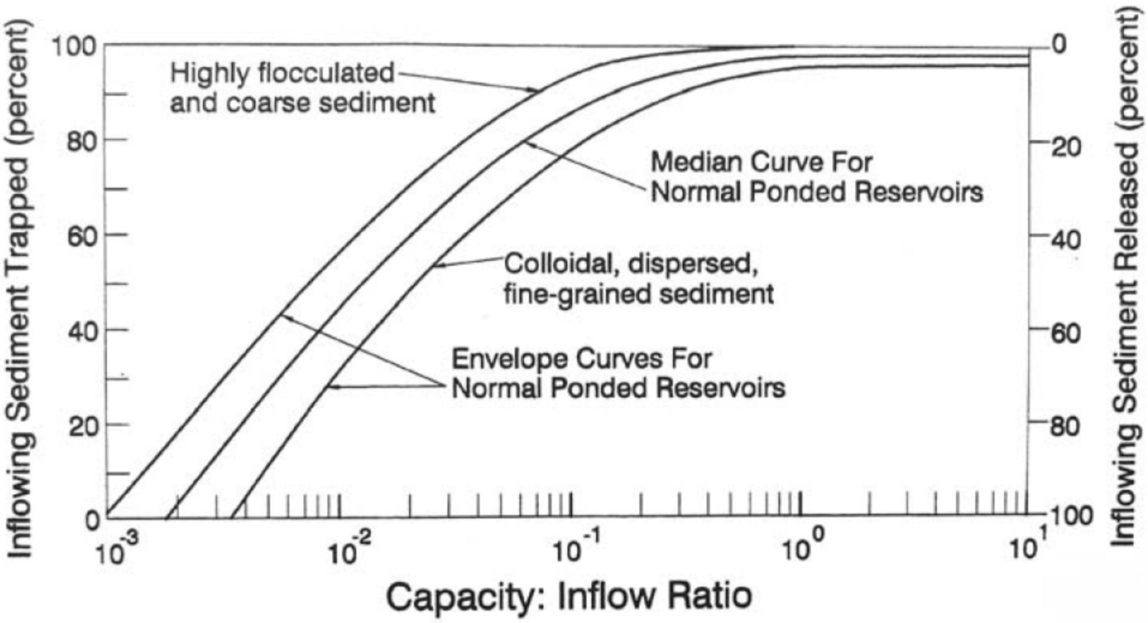


Figure A2.5. The *Brune* [1953] curve for estimating sediment trap efficiency of reservoirs[10].

The volume of sediment deposition in *SedSim* is computed as the ratio of trapped sediment mass to the average sediment density. Xue et al., 2010 report the density of sediment in the Vietnam Delta to be about 1.2 g/cm^3 or 1200 kg/m^3. The model assumes that sediment volume remains stable in the reservoir, thus ignoring any compaction processes.

Of the remaining sediment, which is assumed to be of equal concentration throughout the reservoir volume, some is discharged due to the reservoir water release during the time period, after which a final concentration is computed that accounts for evaporation losses. The *SedSim* model carefully accounts for the impact of sedimentation on reservoir storage volume. As sediment mass accumulates behind the reservoir during a time step, the maximum volumes of water that can be maintained in the dead and active storage zones are reduced in the next time step. This may reduce the total residence time and hence the sediment trapping efficiencies. It can also alter the release of water needed to achieve a specified storage volume or head.

Sediment Management

The *SedSim* model simulates several forms of sediment management in reservoirs, including flushing, bypassing, sluicing, and density current venting. It also can allow for specific pre-specified amounts of sediment removed by hydrosuction, dredging, and sediment excluder devices, but does not simulate those processes. The success of any sediment removal method depends on many factors, including the reservoir channel shape, reservoir water storage volume, reservoir hydraulic conditions, and sediment mobility [*White*, 2000; *Morris and Fan*, 1998].

[10] Figure taken from *Morris and Fan* [1998].

Once a decision is made that a particular sediment removal method is feasible for a particular reservoir it can be implemented in the *SedSim* model but this model is not capable of determining what sediment management techniques are technically and economically feasible for a particular reservoir. Rather, the *SedSim* model will simulate a sediment technique the user indicates should be simulated, without making any judgment about whether such a management practice appears to be reasonable for each reservoir. Such feasibility decisions should be made using a combination of expert judgment and a pre-feasibility sediment screening tool such as the *RESCON* model (short for REServoir CONservation) [*Palmieri et al.*, 2003].

The specific approach taken by *SedSim* to simulate each of these methods is discussed in below. However, before discussing *SedSim*'s approach to simulating specific sediment management techniques, and the data requirements for the user to do so, it will first be of value to briefly discuss how the methods *SedSim* simulates fit in among the range of techniques that are available for sediment management in reservoirs. This is depicted in Figure A2.6. A variety of options are available for managing sediment in reservoirs, and they generally fall into three categories: minimizing sediment inflow (e.g., catchment management), preventing sediment that does enter the reservoir from depositing (sediment routing), and removing sediment after it has deposited (sediment removal) [*Annandale*, 2013]. Other options include designing the reservoir such that it is large enough to handle significant accumulation of sediment during the desired operating period, and designing the reservoir so that sediment accumulation occurs in specific areas that permit future removal [*Morris and Fan*, 1998]. (Note that these techniques are not generally exclusive, in the sense that multiple techniques can be often be applied at a particular reservoir, such as routing during times of high sediment inflows and removal during other times of year). *SedSim* allows simulation of sediment routing and sediment removal (see Figure A2.6), because these methods offer the opportunity to preserve a river basin's erosion and sediment transport characteristics, which are important for ecosystem health and productivity, rather than simply focusing on preventing sediment deposition in reservoirs as a means of reducing impacts of sedimentation on hydropower operations. For example, catchment management refers to practices that reduce sediment flowing into the reservoir of interest, which could include re-vegetation, tillage practices (e.g., contour farming), and structural approaches (e.g., check dams located upstream to prevent sediment deposition in a downstream dam). In the Mekong Basin, for which *SedSim* was created, it is important not to reduce high sediment loads, but instead to preserve sediment transport processes as well as preventing sedimentation.

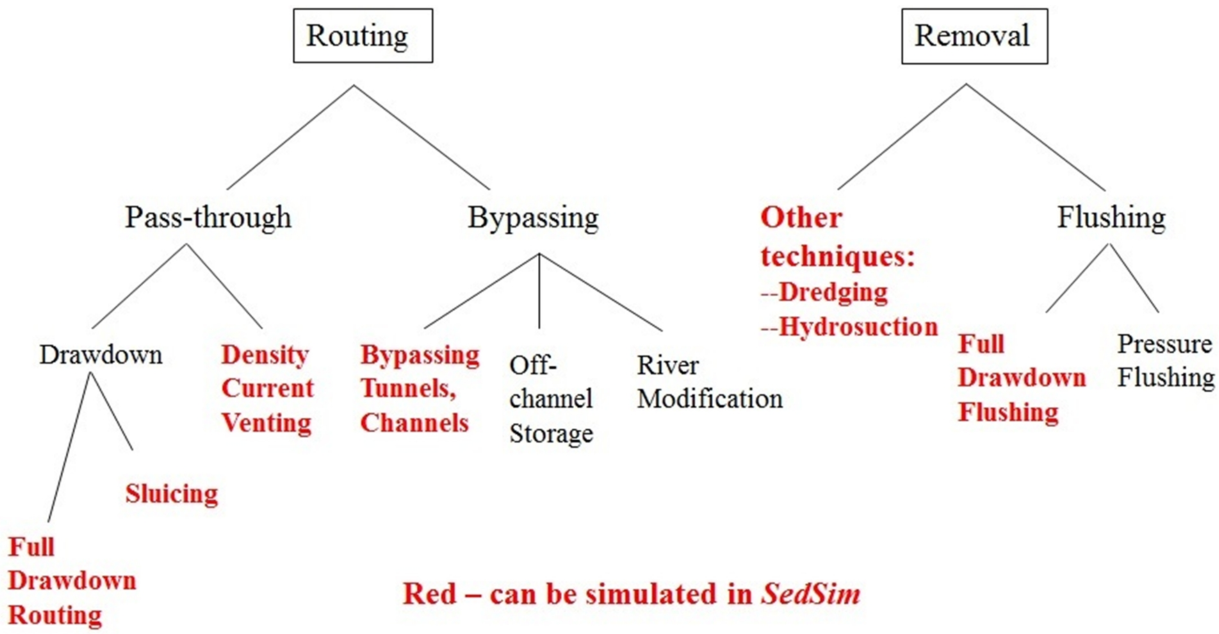


Figure A2.6. Summary of techniques commonly implemented to control reservoir sedimentation. Techniques in bold red type can be simulated (or accounted for in the case of "other techniques") in *SedSim*.

The difference between sediment routing and sediment removal is quite distinct: The goal of routing is to prevent deposition to the extent possible by hydraulically routing the sediment beyond the reservoir, whereas sediment removal focuses on removing previously deposited sediment. In this sense, sediment routing is advantageous in that regularly performed routing can produce reservoir sediment outflows that are consistent in timing and concentration with the natural sediment inflow regime. To prevent deposition, sediment routing seeks to manage the sediment-laden portion of reservoir inflows differently than the clear portion, and is generally done in one of two ways: sediment bypassing and sediment pass-through. Sediment bypassing routes the sediment-laden water around the reservoir to prevent deposition, whereas sediment pass-through routes the water through the reservoir by maintaining a high sediment transport capacity.

Both sediment bypassing and sediment pass-through are implemented during high flow events, which in most parts of the world is when the majority of the annual sediment load is transported. Common examples of bypassing include bypass tunnels (e.g., the Miwa Dam bypass system in Japan), river modification (e.g., Nagle Reservoir in South Africa), and off-channel reservoir storage (e.g., Fajardo Dam in Puerto Rico) [*Annandale*, 2013]. The extent to which hydropower production is affected by these practices depends on the conditions at the site. Certainly, if significant quantities of water are bypassed around the reservoir during high flow periods to transport sediment around the reservoir, less water is stored in the reservoir and benefits from storage are reduced. However, if the reservoir is properly designed from the beginning, then reduced inflows are anticipated and planned for, as are the associated losses in power output and water yield. While some forms of sediment bypassing can require expensive infrastructure such as bypass tunnels, sediment pass-through almost always requires inclusion of sediment management infrastructure in the dam itself (such as mid- and low-level outlets), which is much less costly when included in the initial design.

Common examples of sediment pass-through include sluicing (e.g., First Falls Dam in South Africa) and density current venting (many applications are in China, including Xiaolangdi Dam), both of which pass sediment directly through the dam via different combinations of outlets. Sluicing is not as commonly implemented as sediment management techniques such as flushing, so establishing the suitability of a particular site and dam for sluicing is not as straightforward. The goal of sluicing is to maintain a sediment balance, such that the annual sediment inflow equals the annual sediment outflow. Thus, sluicing is more successful when performed annually. This is accomplished by partially drawing the reservoir down during times of high sediment inflow to increase the energy slope (and sediment transport capacity). This drawdown may be done seasonally for long durations, or for individual flood events. The impact of sluicing on hydropower production depends on several factors, including: whether or not power production is even possible during sluicing, which depends factors such as concentration of sediment, quartzite content in sediment (hardness), and duration of sluicing; the extent of drawdown (reduction in head) required to achieve the desired increase in transport capacity; and the duration of sluicing.

While sluicing is likely the most applicable sediment pass-through technique for the Mekong basin that involves some drawdown of the reservoir, other drawdown pass-through techniques are used elsewhere. For example, a reservoir may maintain very low storage for most of the flood season to permit sediment passage, as is practiced at Sanmenxia Dam in China [*Wang et al.*, 2005]. This approach may seem similar to drawdown flushing, but is different because the sediment is being discharged before it can settle, and is thus released in a manner that is more consistent with the natural sediment regime. This, just like sluicing, can be scheduled to occur on a seasonal basis (e.g., every year during the flood season), or can be implemented during individual flood events, which may be more applicable in smaller reservoirs that have the capability to monitor in real time the sediment and water flows in the basin upstream of the reservoir. On the other hand, the goal of density current venting is to take advantage of high-density plumes of sediment (called density currents) that may form at times as sediment flows into a reservoir. Depending on the flow, concentration, and temperature characteristics at a particular site during a particular event, a density current may form. If and when the current forms, it can be released through the dam's low-level outlets upon reaching the base of the dam, generally without significant impacts on hydropower operations given the relatively low quantity of water that is released during this process.

Another option for managing sediment in a reservoir is sediment removal. There are two categories of such methods. The first is to physically remove sediment from the reservoir and place it elsewhere (e.g., into the downstream channel). Examples include dredging; use of an inline sediment collection device; draining the reservoir and performing dry excavation; and hydrosuction, which siphons sediment from the bottom of the reservoir to the downstream channel. Some of these methods (e.g., dredging) are typically very expensive, in some cases approaching the cost of building a new dam. Others (e.g., hydrosuction) are only applicable to short reservoirs [*Palmieri et al.*, 2003]. While *SedSim* does not explicitly simulate these techniques, it does allow for the removal of a specified quantity of sediment mass from a reservoir over a specified period of time without any changes to reservoir operations, which is an adequate representation of several of the management techniques described above (e.g., dredging, but not dry excavation).

The second category of sediment removal is to implement sediment flushing, of which there are several types. The purpose of sediment flushing is to remobilize and remove sediment that has been previously deposited in the reservoir [*Atkinson*, 1996]. This can reduce losses in reservoir water storage capacity; and can increase sediment loads being discharged downstream. Flushing is conducted by opening low level (and often mid-level) flushing gates. This causes an increased flow of water through the reservoir, resuspending deposited sediment and discharging both through the gates. There are two kinds of flushing: drawdown flushing (free flow flushing) and pressure flushing (partial drawdown flushing) [*Atkinson*, 1996; *White*, 2001; *Palmieri et al.*, 2003]. The *SedSim* model only simulates drawdown flushing, but the differences between these two approaches are clarified in the section below that is dedicated to flushing in *SedSim*.

If sluicing and flushing are to be performed annually, the significant difference between the two approaches is in the timing of sediment release. Sediment flows may be more naturally preserved with sluicing, whereas a sudden release of sediment over a shorter period of time may result with flushing. However, sluicing is more likely to remove only the finer fractions of sediment, whereas flushing can remove sediment sizes up to sand and gravel (depending on the magnitude of the flushing flow that is employed).

Flushing

The purpose of sediment flushing is to remobilize and remove sediment that has been previously deposited in the reservoir [Atkinson, 1996]. This can reduce losses in reservoir water storage capacity; and can increase sediment loads being discharged downstream. Sediment in river flows impacts the river's geomorphological makeup and ecosystem habitats. Flushing is conducted by opening low level flushing gates. This causes an increased flow of water through the reservoir, resuspending deposited sediment and discharging both through the gates. There are two types of flushing: drawdown flushing and pressure flushing [*Atkinson*, 1996; *White*, 2001; *Palmieri et al.*, 2003]. The *SedSim* model only simulates drawdown flushing. Each will be discussed separately next.

Drawdown flushing requires reducing water levels in the reservoir enough to permit free flow conditions through the low level outlets. For this to happen the low level outlets should be located near the original river bed elevation, and should have the capacity to discharge streamflow during the flushing period without significant ponding behind the dam [*Palmieri et al.*, 2003]. Drawdown typically begins at the beginning of the high flow season after a period of low inflows and hence low storage volumes. The high flows through the reservoir are more effective in resuspending sediment than low flow values. Low reservoir water levels must be maintained during the flushing period. Thus, drawdown flushing is typically performed at the beginning of the high flow season. The appropriate recurrence interval for flushing depends on the conditions at the reservoir site. Regularly performed flushing, if conducted at the right time, can be more environmentally beneficial than less regularly performed flushing. This is because the amount of sediment released during each flushing event may contain sediment concentrations (and durations of those concentrations) that more closely resemble the river's natural high-flow sediment conditions, in comparison to flushing events designed to discharge sediment that has collected over much longer periods of time. However, more frequent flushing results in more reductions in hydropower production and hence power reliability is lower.

Pressure flushing is not included in the *SedSim* model. It is different from drawdown flushing in that much higher water levels are maintained in the reservoir during pressure flushing. While avoiding drawdown of the reservoir to very low storage levels may permit increased hydropower production in comparison to drawdown flushing, pressure flushing is only effective at remobilizing and discharging sediment located in the vicinity of the low level flushing outlet, as well as relocating sediment from upstream portions of the reservoir to downstream portions of the reservoir. In general, drawdown flushing is capable of removing larger quantities of sediment, and from more locations in the reservoir, than pressure flushing.

Simulating Flushing in the *SedSim* Model

The following information must be supplied by the user for every reservoir at which sluicing will be simulated. Some user inputs are described below as *Optional*, meaning these inputs are extra features that are not required to run a simulation. More details on these inputs are provided in the discussion of “Flushing” worksheet, where most of these inputs are required to be entered.

1. Target flushing start date. *Worksheet*: “Flushing”.

2. Flushing duration. *Worksheet*: “Flushing”.

3. Minimum inflow rate required to initiate drawdown for flushing after the date specified above (*Optional)*. *Worksheet*: “Flushing”.

4. Target water surface elevation during flushing. *Worksheet*: “Outlet Capacity Data”. This is the water surface elevation target during drawdown and flushing. *SedSim* will establish this value by importing the first elevation in the low-level outlet capacity-discharge table, which should represent the elevation of the low level outlet). This is generally close to the original river bed elevation.

5. Maximum water surface elevation (WSE) that will still result in successful flushing. *Worksheet*: “Flushing”.

6. Minimum discharge through the low level outlets that will still result in successful flushing. *Worksheet*: “Flushing”.

7. Maximum flushing drawdown rate (*Optional)*. *Worksheet*: “Flushing”.

8. The representative reservoir bottom width close to the dam. (This information is used to determine how much sediment is removed during flushing. More details are available later in this section). *Worksheet*: “Flushing”.

9. The representative (average) side slope of the reservoir banks. (This information is used to determine how much sediment is removed during flushing. More details are available later in this section). *Worksheet*: “Flushing”.

10. The representative bottom width of the flushing channel. (*The model will calculate this as a function of other inputs described above if the user does not have this information*). *Worksheet*: “Flushing”. This information is used to determine how much sediment is removed during flushing.

11. The representative (average) side slope of the flushing channel banks. (*The model will calculate this as a function of other inputs described above if the user does not have this information*) *Worksheet*: “Flushing”. This information is used to determine how much sediment is removed during flushing.

12. Coefficient value, k, for sediment load generation during Flushing, used in equation kQ^m (*Optional). Worksheet*: “Flushing”. (Instead of computing the sediment loads discharged during flushing via the methods described below in this section, the user can instead specify parameters to be used in the equation kQ^m to determine sediment discharge from the reservoir each day during flushing as a function of reservoir outflow).

13. Exponent value, m, for sediment load generation during Flushing, used in equation kQ^m (*Optional*). *Worksheet*: “Flushing”. (Instead of computing the sediment loads discharged during flushing via the methods described below in this section, the user can instead specify parameters to be used in the equation kQ^m to determine sediment discharge from the reservoir each day during flushing as a function of reservoir outflow).

14. A discharge capacity vs. elevation table for the low level outlet that will be used for flushing. *Worksheet*: “Outlet Capacity Data”.

The *SedSim* model flushing procedure consists of three components: Drawdown, Flushing, and Refill. The user must supply inputs related to these three processes, all of which are described below and depicted in Figure A2.7, which demonstrates an example of *SedSim* simulation results for reservoir water storage during flushing.

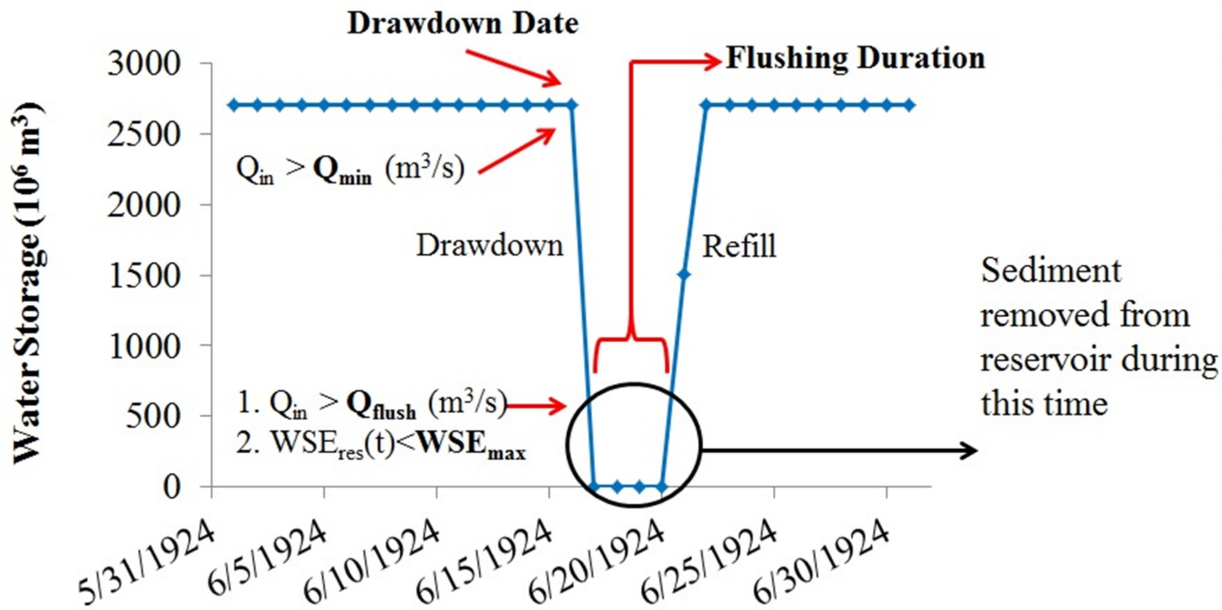


Figure A2.7. Depiction of the flushing process in *SedSim*. This figure plots simulation results for an example reservoir being flushed. In the figure, $Q_{in}(t)$ represents the reservoir inflow in time period *t*, Q_{flush} represents the minimum flow required to achieve successful flushing, Q_{min} represents the minimum inflow required before reservoir drawdown is initiated, $WSE_{res}(t)$ represents the water surface elevation in the reservoir in period *t*, and WSE_{max} represents the maximum reservoir water surface elevation for flushing to be successful (typically this is equal to or within a few meters the elevation of the low level flushing outlet).

On or after the date on which the user specifies drawdown is to be initiated, the *SedSim* model initiates the drawdown process once the reservoir inflow exceeds the minimum inflow target set by the model user. (In other words, the user can establish a minimum reservoir inflow required to initiate drawdown that is different from the minimum inflow/outflow required to achieve successful flushing. The reservoir's low level gates are opened to attempt to draw down the reservoir to the lowest possible storage so flushing can occur. (The model assumes these gates are already installed). The low level gates are only opened when flushing is to be attempted, and they are closed as soon as flushing is complete. Other outlets can be used to drain the reservoir during the drawdown period, including the hydropower outlets, as long as the reservoir's water surface elevation during the time period of interest is large enough that the outlet has discharge capacity. Beginning with the first day of reservoir drawdown, the reservoir's pre-established operating policy is temporarily overridden to conduct flushing. In other words, the model does not require the user to modify the pre-existing operating policy (e.g., elevation targets, storage targets, or other policy data) during the time period over which flushing is to occur. Rather, during the time frame when flushing is to occur, flushing is assumed to be the primary goal of operation, and the model operates the reservoir to attempt to satisfy flushing criteria, which are discussed below. The duration of drawdown is not specified by the user, but instead depends on the water storage at the start of drawdown, the maximum drawdown rate, and the capacity of the reservoir's outlets to release water as the reservoir is drained.

During the drawdown process, the Trapping Efficiency (TE) of the reservoir is assumed to be zero. Similar to normal reservoir operations, the only sediment that can be released from the reservoir during drawdown is sediment contained in suspension in the reservoir water volume. That is, no sediment is removed from the sediment mass that has previously settled to the bottom of the reservoir. Water is released from the reservoir only through outlets that have capacity given the reservoir's water surface elevation.

The goal is to keep the reservoir's storage volume as low as possible, so as not to exceed the maximum water surface elevation required to achieve successful flushing (as defined by the user).

Flushing is assumed to begin on the first date on which the following criteria are satisfied at the reservoir:

1. The water surface elevations (mamsl) at the beginning and end of the time period do not exceed the maximum flushing water surface elevation specified by the user.
2. The flushing discharge (discharge through the low level outlets) exceeds the minimum flushing discharge requirement (m^3/s).

Once these criteria have been satisfied for the number of days over which the user specifies flushing should occur, flushing is complete and refill begins in the next time period. If either constraints are not satisfied on a particular day, then a day is added to the number of specified flushing days. If flushing requirements fail to be satisfied, no sediment is removed from the deposited sediment mass, although already suspended sediment can be discharged from the reservoir via the low level outlets, or can remain in suspension in the water stored in the reservoir. The model will continue to attempt to satisfy the flushing requirements until the specified number of flushing days has occurred. Due to the significant uncertainty in estimating the discharge requirements to achieve successful flushing, the model assumes that if the flow constraints are satisfied to within 20% of the provided values, flushing is successful.

During the flushing period, the TE of the reservoir is assumed to be zero. The volume of sediment that is removed from the reservoir as a result of flushing is removed from the settled sediment mass and is equally distributed in the discharge downstream over the user-specified flushing horizon. No more sediment mass than is available can be removed from the reservoir as a result of flushing. Sediment is assumed to be removed from segments of the elevation-volume-area curve in the same manner in which sediment was assumed to deposit in the reservoir. For example, if sediment is deposited linearly throughout the elevation range, then flushing will result in removal of sediment from all elevations in the same manner. The quantity of sediment removed during each flushing event is determined via a process that is described at the end of this section on flushing. Flushed sediment accumulates downstream of the flushing channel and is subject to being picked up and further transported downstream depending on the unsatisfied sediment carrying capacities of the reach flows.

During the flushing period, only those outlets that maintain a positive release capacity at the reservoir's water surface elevation each day can be used to release water and sediment. Generally, only the low level outlets will have discharge capacity at such low elevations, thus preventing any hydropower production during flushing. The water surface elevation cannot drop below the minimum elevation at which the low level outlet has capacity to release water. Thus, if any water remains in storage below the low-level outlet, which is not likely to be much water given that the low level outlets are best positioned near the original river bed elevation, the low level outlets would not have capacity to release this water. Any storage or elevation target set to a level below the low level outlet will result in a surface elevation close to that of the low level outlet.

Note that the goal of maintaining low storage during flushing does not mean that zero water volume is maintained in the flushing channel; rather, this means that water volume inflow is similar to water volume outflow during the time period. The goal of flushing is to permit free flow through the reservoir. Thus, at the beginning and end of every time period during which flushing occurs, in a real reservoir some water will always exist in storage in the flushing channel, because there is a constant flow of water into and out of the channel throughout the day. However, one result of conducting a daily mass balance in the reservoir without routing is that all water flowing into the reservoir each day is assumed to be immediately available for release, with storage recorded only at the beginning and end of each day. During the flushing period, this effectively results in all of the inflow being stored immediately behind the dam, and the low level outlet thus has the capacity (and the goal) of releasing the stored water right away. This means that during flushing, while a storage close to zero m^3 is recorded at the beginning and end of each day, in a real reservoir there is storage of water maintained within the flushing channel throughout the flushing period.

The refill period begins on the day after drawdown is completed (i.e., the day after the drawdown maximum elevation and minimum discharge goals have been satisfied for the specified number of days). The reservoir's pre-established operating policy is re-established during the refill period. For example, if the reservoir has a pre-established water storage or water surface elevation target for the day after flushing is completed, the reservoir will not release any water until this target is met. Hydropower production is possible during refill, but only once the water surface elevation is high enough to permit a turbine outlet discharge capacity greater than zero.

Next, note that density current venting, flushing and sluicing are assumed to be exclusive activities, in that they cannot be conducted at the same time. Multiple sediment management techniques can be simulated in the same reservoir at different times. However, flushing, sluicing and density current venting cannot be simulated concurrently. Any management technique being simulated will be allowed to finish before a new technique is begun. For example, If sluicing is being simulated at a particular reservoir and flushing is meanwhile scheduled to occur, the start of flushing will be delayed until sluicing is completed. If the user schedules two or more sediment management techniques to start on the same date, priority is given first to flushing, then to sluicing, and finally to density current venting.

The *SedSim* approach to determining the quantity of sediment removed during a flushing event is as follows.

1. During each time step, determine the deposited sediment volume, $V_d(t)$

2. During each time step, determine the depth of the deposited sediment layer, *d(t)*.

To accomplish Step 2, *SedSim* first determines the average Area, *A*, over which the sediment is deposited during the time step. This value is taken to be constant for the duration of simulation. This is estimated using the average surface area of the reservoir, or

$$A = \frac{V_T}{E\ _a - E\ _b} \quad \text{(A2.4)}$$

where *A* is the average water surface area in the reservoir, V_{TK} is the reservoir's total storage capacity, El_a is the elevation at the top of the active storage zone, and El_b is the elevation at the bottom of the reservoir (likely the original river bed elevation). These two values will be taken from the user-specified elevation-volume table.

The area, A, is then used to determine the depth of the deposited sediment layer, *d(t)*, as follows:

$$d(t) = \frac{V_d(t)}{A} \quad \text{(A2.5)}$$

(Note: This approach is a simplification. In reality, in each time step the sediment is deposited over the reservoir water surface area, which changes in each time step).

3. Determine the fraction of the sediment layer deposited in time period *t* that sits within the incised channel to be formed by flushing, which represents the quantity of sediment that can be removed via flushing.

Every flushing event results in removal of some fraction of the volume of sediment that has settled since the last flushing event. If the reservoir reaches its sustainable long-term storage capacity, K_f, which is determined in *SedSim*, the model assumes that all of the sediment that has settled since the last event can be removed. The Long Term Capacity Ratio (LTCR) (see *Atkinson* [1996] for more details) represents the ratio of the long term storage capacity that can be sustainably maintained (in perpetuity) with frequent and successful flushing, K_f, to the initial storage capacity, K_o, as given by the following:

$$L \qquad = \frac{K_f}{K_o} \quad \text{(A2.6)}$$

Figure A2.8 represents a simplified version of a reservoir's cross-sectional geometry that enables a quick calculation of the LTCR of any reservoir that will be frequently flushed. In this figure, the area within the inner trapezoid (denoted by the letter "B") represents the cross-sectional area that can be maintained in perpetuity by frequent and effective flushing. (Note that this sustainable area is assumed to extend the length of the reservoir, thus forming a sustainable storage volume.) The area of the outer trapezoid (denoted by the letter "A") represents the total representative cross-sectional area of the reservoir. While the flushing bottom elevation

(elevation of low level outlet) is higher than the reservoir bed elevation at the dam (original river bed elevation) in this figure, the user can locate the low level outlet at the bottom elevation of the dam, in which case the bottom of the flushing channel coincides with the bottom of the dam.

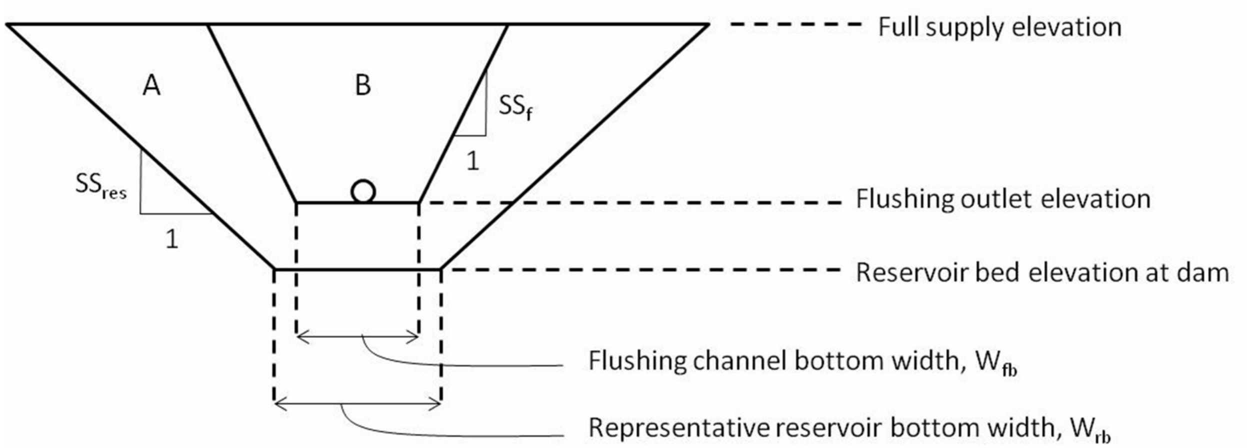


Figure A2.8. Simplified cross-sectional geometry of a reservoir (outer trapezoid) and the sustainable channel (inner trapezoid) that can be formed by frequent and effective flushing.

The ratio of the two areas "B" and "A" in Figure A2.8 defines the LTCR, or

$$L = \frac{B}{A} \tag{A2.7}$$

Note that *SedSim* accounts for many possibilities regarding the geometries of areas "A" and "B". For example, *SedSim* accounts for the circumstance in which the flushing channel side slope is low enough that the flushing channel will eventually meet the side of the simplified reservoir geometry before the flushing channel reaches the top of the reservoir.

SedSim tracks the evolution of the flushing channel as sediment layers deposit within the reservoir in each time step. When the flushing channel has finally reached its sustainable storage capacity (given by the product of the area "B" in Fig 2.8 and the reservoir length), flushing is capable of removing all of the sediment that has deposited since the previous flushing event. Also, if the flushing channel has the potential to be larger than the reservoir's geometry from the start (i.e., "B" is greater than "A" in Figure A2.8), then complete removal of settled sediment is possible throughout simulation. Generally, it takes some time for enough sediment accumulation to occur before a reservoir reaches the LTCR. Thus, if a reservoir that is regularly flushed has not yet reached its LTCR, the fraction of settled sediment that is removed during a particular flushing event is assumed to be equal to the ratio of the current flushing channel top width in the simplified reservoir geometry, $W_f(t)$, to the width of accumulated sediment deposits in the simplified reservoir geometry, $W_s(t)$. The assumption is that sediment deposits in an equally-distributed manner within this simplified reservoir geometry. Thus, a fraction of any deposited sediment layer will fall within the confines of the channel formed by flushing and will thus be removed when flushing occurs, whereas the rest of the sediment will be located outside of the flushing channel boundary and will thus never be removed. In equation form, the fraction of the mass, $f_m(t)$ in a sediment layer deposited in a reservoir in time period t that can be removed in the next flushing event is given by the following relationship

$$f_m(t) = \frac{W_f(t)}{W_s(t)} \tag{A2.8}$$

Given that the layer of sediment deposited outside the confines of the flushing channel is growing as the simulation proceeds and more sediment accumulates, and given that the flushing channel geometry and reservoir geometry have different bottom widths and side slopes, the fraction in Eq. (A2.8) can change in every time step. The fraction may increase or decrease depending on the relative shapes of the cross-sectional geometries.

The widths in Eq. (A2.8) above is depicted in Figure A2.9 below.

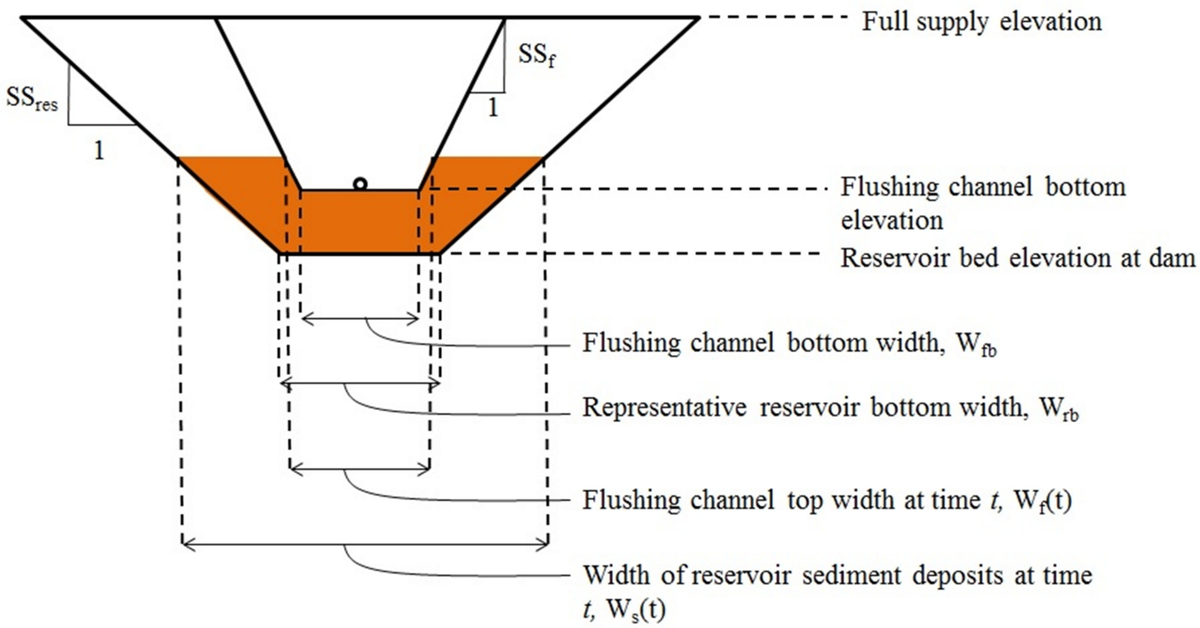


Figure A2.9. Simplified cross-sectional geometry of a reservoir (outer trapezoid) and the sustainable channel (inner trapezoid) that can be formed by frequent and effective flushing. The brown are represents an example of sediment that has previously deposited in the reservoir up to time period *t*. Only the fraction of any newly deposited sediment layer in time period *t+1* that deposits within the boundaries of the theoretical flushing channel will be removed in the next flushing event.

Bypassing

Bypassing divides the flow into two parts. The bottom portion flows into the reservoir and the top portion gets bypassed to a point downstream of the reservoir outlet. Bypassing can be implemented any time but is usually implemented when the flow is high, and hence carrying more sediment than a lower flow would. All sediment and flow directed into the bypass are discharged into the downstream channel without any routing considered.

To implement bypassing in the *SedSim* model the user must specify the minimum inflow rate (m^3/s) when bypassing would start, and the maximum bypass discharge capacity. Bypassing is assumed to start when the total reservoir inflow (before bypassing is considered) equals or exceeds that minimum specified inflow rate, and stops when the inflow rate drops below the specified minimum inflow rate. Only inflow in excess of the minimum inflow rate is bypassed, with the remainder entering the reservoir. However, when the reservoir inflow in excess of the minimum bypass flow rate also exceeds the maximum bypass discharge capacity, the flow in excess of the discharge capacity also enters the reservoir. The default model assumption is that sediment is partitioned between the bypass and reservoir in proportion to the fractions of total inflow that are distributed into the bypass and reservoir. If desired, the user can specify what fraction of the sediment that would otherwise have entered the reservoir (based on the proportion of total inflow that enters the reservoir) should instead be distributed into the bypass. This option was implemented to reflect that concentration increases with depth of flow, and thus the bypass may remove more of the inflowing sediment than just the proportion of flow diverted into the bypass.

To further explain this reservoir inflow fraction assumption, suppose for a particular reservoir that the minimum bypass flow is 50 m^3/s, the bypass capacity is 80 m^3/s, and the total inflow is 120 m^3/s. Since the inflow exceeds the minimum flow requirement, a bypass will occur. All flow in excess of the minimum threshold will be bypassed, or 120 m^3/s – 50 m^3/s = 70 m^3/s. The remaining 50 m^3/s will enter the reservoir. At least 70/120 = 0.583 (58%) of total sediment inflow (kg) will be bypassed. However, by specifying a bypass fraction in the user interface, the user can establish what fraction of the remaining 42% of the sediment load will be diverted into the bypass instead of entering the reservoir. If the user enters no fraction (0%), this corresponds to the default assumption, which is that all of the remaining 42% of sediment flows into the reservoir. If the user chose, for example, 50% instead, in this example the bypass would receive 58% + 0.5*42% = 79% of the total sediment load, while the reservoir would receive the remaining 21%.

The following information must be supplied by the user for every reservoir at which bypassing will be simulated. More details on these inputs are provided in the discussion of the sediment management specifications worksheet (“Bypassing”), where these inputs are required to be entered.

1. Minimum Bypass flow rate (m^3/s). *Worksheet*: “Bypassing”. Minimum reservoir inflow rate at which the sediment bypass is opened and sediment and flow begins to be discharged around the reservoir.

2. Bypass discharge capacity (m^3/s). *Worksheet*: “Bypassing”.

3. Fraction of sediment load in reservoir inflow (*SedSim will establish a default value if the user does not specify a value*). *Worksheet*: “Bypassing”. Allows the user to describe how sediment is partitioned between the bypass, which diverts sediment around the reservoir, and the remaining sediment that enters the reservoir.

Sluicing

When the simulation date reaches a user-specified beginning date of sluicing, the reservoir will be drawn down to the associated user-specified water surface elevation (mamsl) target, permitted that all optional inflow rate and concentration conditions (described below) are met. Note that density current venting, flushing and sluicing are assumed to be exclusive activities, in that they cannot be conducted at the same time. Any management technique being simulated will be allowed to finish before a new technique is begun. For example, if sluicing is being simulated at a particular reservoir and flushing is meanwhile scheduled to occur, the start of flushing will be delayed until sluicing is completed. If the user schedules two or more sediment management techniques to start on the same date, priority is given first to flushing, then to sluicing, and finally to density current venting.

While the reservoir is drawn down to the target level, the drawdown rate (m/day) will be restricted to the user-specified maximum rate. On the beginning date of sluicing, and for the duration of sluicing, sediment trapping is defined by the Churchill curve (see below for more discussion). When the simulation date reaches the day after the user-specified sluicing end date, normal sediment trapping will resume (Brune's curve trapping), unless another form of trapping is activated immediately after the completion of sluicing. During sluicing, even if the reservoir cannot be drawn down to the target elevation on a given day, sluicing is still assumed to successfully occur. Thus, if drawdown takes a significant amount of time compared to the total sluicing duration, a significant percentage of the sluicing period could consist of drawdown.

If the user specifies that no hydropower will be produced during sluicing, then only the mid- and low-level gates can be used to drain the reservoir (not the hydropower outlets). If the user specifies that hydropower production is possible during sluicing, then water will be released through the hydropower outlets throughout the sluicing process, assuming the hydropower outlets have capacity to release flow.

Once the reservoir is drained down to the target sluicing elevation, the mid-level outlets and low-level outlets are used to achieve sluicing. The low-level outlets are only used during sluicing if (1) the inflow is too high for the mid-level outlets to release to maintain the target elevation, and (2) the water surface elevation is below the user-specified maximum water surface elevation at which low level outlets can be used. If the low-level outlets are used to release water during sluicing, *SedSim* assumes that no sediment is released as a result of scour in the vicinity of the low-level outlet.

The *Churchill* [1948] Curve, which appears in Figure A2.10, is used to determine trap efficiency during the sluicing period (on or in between the beginning and ending dates of sluicing). A new trap efficiency value is computed every day depending on the residence time of water in the reservoir. The Churchill Curve is used instead of the Brune Curve because it produces improved sediment passage approximation for reservoirs that have been drawn down, and are therefore hydrologically smaller than during normal operations.

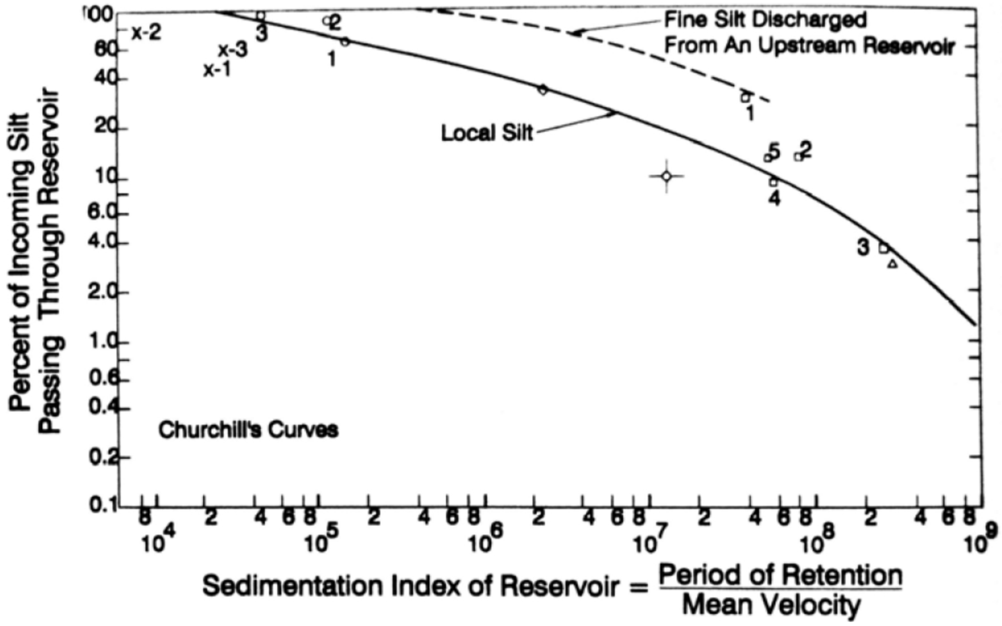


Figure A2.10. The *Churchill* [1948] Curve for estimating sediment release efficiency (100-trap efficiency)[11].

The Sedimentation Index (SI) is used to predict the percentage of sediment predicted to pass through the reservoir (or 1 - TE), and is given by the following:

$$S\ (t) = \frac{R(t)}{v(t)} = \frac{\frac{S(t)}{Q_O(t)}}{\frac{Q_O(t)}{A(t)}} = \frac{\frac{S(t)}{Q_O(t)}}{\frac{Q_O(t)}{\frac{S(t)}{L}}} = \frac{\frac{S(t)}{Q_O(t)}}{\frac{Q_O(t)}{\frac{S(t)}{L}}} = \frac{\left(\frac{S(t)}{Q_O(t)}\right)^2}{L} = \frac{\frac{S(t)}{Q_O(t)}}{\frac{Q_O(t)}{A(t)}} \quad \text{(A2.9)}$$

where *R(t)* is the residence time (s) of water in the reservoir during the time period *t* (one day); *S(t)* is the water storage (m^3) in the reservoir at the beginning of the time period; $Q_o(t)$ is the reservoir release rate (m^3/s) during the time period; *A(t)* is the cross-sectional area (m^2) through which the reservoir inflow is discharged during the time period; *L* is the reservoir length (m).

The SI(t) is then used to determine the percentage of sediment passing, *P(t)*, through the sluiced reservoir by applying the following approximation to Churchill's original regression curve:

$$P(t) = 800*(SI(t)/3.28)^{-0.2}-12$$
$$TE = (100 - P(t))/100 \quad \text{(A2.10)}$$

The following information must be supplied by the user for every reservoir at which sluicing will be simulated. Some user inputs are described below as *Optional*, meaning these inputs are extra features that are not required to run a simulation. More details on these inputs are provided in the

[11] Figure taken from *Morris and Fan* [1998].

discussion of the sediment management specifications worksheet ("Sluicing"), where most of these inputs are required to be entered.

1. Beginning date of sluicing. *Worksheet*: "Sluicing".

2. Sluicing starting criterion: minimum reservoir inflow rate (m^3/s) (*Optional*). *Worksheet*: "Sluicing".

3. Ending date of sluicing. *Worksheet*: "Sluicing".

4. Target drawdown water surface elevation (mamsl) or storage (m^3). *Worksheet*: "Sluicing".

5. Maximum sluicing drawdown rate (m/d) (*Optional*). *Worksheet*: "Sluicing".

6. Maximum sluicing refill rate (m/d) (*Optional*). *Worksheet*: "Sluicing".

7. Reservoir Length (m). Worksheet: "Reservoir Specifications".

8. Does hydropower production occur during sluicing? (Yes or No.) *Worksheet*: "Sluicing".

9. Mid-level outlet elevation vs. discharge capacity table. Worksheet: "Outlet Capacity Data". This table will be used to limit the capacity to release water from the mid-level outlets during sluicing based on reservoir water surface elevation. Note that this input is not optional, as the model makes the assumption that mid-level outlets are required to conduct sluicing.

<u>Density Current Venting</u>

The following are some important assumptions *SedSim* makes in simulating density current venting. First, There is no user-specified start date for venting. Instead, it can occur on any day, at any time of year. It begins whenever the combination of inflow rate and sediment concentration result in a theoretical venting efficiency that exceeds the use-specified minimum venting efficiency (defined below). Likewise, there is no user-specified end date for venting. Instead, venting ends whenever the combination of inflow rate and sediment concentration result in a theoretical venting efficiency that is less than the user-specified minimum venting efficiency. (Venting efficiency, which is defined by the user as a function of inflow conditions, describes the percentage of sediment concentration flowing into a reservoir that can be released by the low-level outlets at the dam during density current venting).

Next, if density current venting is initiated in a time period (if the venting efficiency in time period *t* exceed the user-specified minimum venting efficiency), the reservoir maintains its originally specified rule curve, but four user-specified constraints are imposed on the reservoir during this time that may alter the reservoir's targets from their pre-specified course. These constraints are described here. The latter three require user input, as described at the end of this section.

1. The target outflow rate (m^3/s) for the low level outlets $Q_{vent}(t)$, is set equal to the reservoir inflow, $Q_{in}(t)$ (i.e., $Q_{vent}(t) = Q_{in}(t)$). To limit the capacity of the low level outlets to release the inflow during density current venting, the user should establish an elevation vs. discharge capacity table for the low level outlet used for venting.

2. The user can impose a minimum daily power production requirement during venting. Since the inflow rate will be released through the low level outlets during venting, it is important to specify some minimum power production requirement if one exists, because the reservoir may otherwise not produce any power during venting, depending on the current water surface elevation (or storage) target on the original guide curve. Note that any water released from the hydropower outlets during venting will result in some drawdown, given that the inflow is likely being released during this time.

3. Additional water may be released from the reservoir through both the hydropower and mid level outlets, assuming capacity exists, if the user specifies a maximum downstream sediment concentration (mg/l) during venting. The hydropower outlets will not be used to release additional water if their release is diverted away from the reservoir's downstream channel.

4. Density current venting (and all associated density current releases) will be stopped if the reservoir's water surface elevation drops below a user specified minimum water surface elevation.

Additionally, venting efficiency (%) is assumed to be a function of inflow rate (m^3/s) and concentration (mg/l). This means that in one simulation time step (each day) a density current may have a particular set of concentration and potential venting efficiency, whereas on the very next day these two parameters may change due to a change in the inflow conditions. This would be fine if a density current entered and exited the reservoir within each day. However, a density current (1) needs time to proceed from the inflow point to the low level outlets, and (2) will dissipate if the sediment supply driving the current stops (or drops below some threshold). *SedSim* ignores these issues for the sake of simplicity.

Next, note that density current venting, flushing and sluicing are assumed to be exclusive activities, in that they cannot be conducted at the same time. Multiple sediment management techniques can be simulated in the same reservoir at different times. However, flushing, sluicing and density current venting cannot be simulated concurrently. Any management technique being simulated will be allowed to finish before a new technique is begun. For example, If sluicing is being simulated at a particular reservoir and flushing is meanwhile scheduled to occur, the start of flushing will be delayed until sluicing is completed. If the user schedules two or more sediment management techniques to start on the same date, priority is given first to flushing, then to sluicing, and finally to density current venting.

A few additional simplifying assumptions are important to mention. For example, density current venting and sluicing cannot be conducted at the same time. When sluicing is underway, density current venting cannot be activated. Also, no muddy lakes exist at the bottom of the reservoir, from which sediment can be released. Next, the bathymetry of the reservoir's submerged channel does not change over time. Infilling of channel running along the thalweg could lead to decreased effectiveness of current conveyance over time. Next, *SedSim* ignores the multi-dimensional spatial variability in concentration and velocity of currents. Finally, *SedSim* ignores the within-day temporal variability of the inflow and concentration that create the currents.

The following information must be supplied by the user for every reservoir in which density current venting will be simulated. Some user inputs are described below as *Optional*, meaning these inputs are extra features that are not required to run a simulation. More details on these inputs are provided in the discussion of the sediment management specifications worksheet ("Density Current Venting"), where most of these inputs are required to be entered.

1. Minimum venting efficiency (%).*Worksheet*: "Density Current Venting". This represents the lowest acceptable percentage of sediment removal that must occur for density current venting to be an attractive option (e.g., 35%). See below for additional comments regarding determination of venting efficiency in *SedSim*, against which this minimum venting efficiency is compared to determine whether or not to conduct venting in each time step.

2. Minimum reservoir water surface elevation (mamsl) during density current venting (*Optional*). *Worksheet*: "Density Current Venting".

3. Reservoir length (km). *Worksheet*: "Density Current Venting". Used to determine a default minimum venting efficiency value for the user if the user does not specify one.

4. Mid-level outlet elevation vs. discharge capacity table (*Optional*). *Worksheet*: "Outlet Capacity Data". This input is used to limit the capacity to release water from the mid-level outlets during density current venting. Mid-level outlets can be used to release clear water downstream to reduce the concentration of density current releases.

5. Low-level outlet elevation vs. discharge capacity table. *Worksheet*: "Outlet Capacity Data". This table will be used to limit the capacity to release water from the low-level outlets during venting.

6. Maximum concentration (mg/l) of sediment released from reservoir during density current venting (*Optional*). *Worksheet*: "Density Current Venting".

7. Whether to continue venting if maximum specified release concentration is exceeded, or to stop venting. *Worksheet*: "Density Current Venting".

8. Minimum power requirement during density current venting (MW) (*Optional*). *Worksheet*: "Density Current Venting".

9. Reservoir bottom width (m). This input is used to determine venting efficiency during each density current venting event. *Worksheet*: "Density Current Venting".

10. Reservoir bed slope (m/m). This input is used to determine venting efficiency during each density current venting event. *Worksheet*: "Density Current Venting".

Some additional comments are necessary regarding the determination of venting efficiency in *SedSim*. As described below, the *SedSim* internally employs a methodology proposed by *Morris and Fan* [1998] that determines the efficiency with which a current can be vented given a reservoir inflow rate (m^3/s) and inflow concentration (mg/l) on each simulation day. In each time step, if the inflow rate and concentration combine to produce a venting efficiency lower than the user-specified minimum venting efficiency, then density current venting will not occur on that simulation day, and the sediment will settle. Aside from assumptions about flow rate and concentration of inflow, input data/assumptions required to develop this venting efficiency table include temperature (for density calculations), grain size distribution, river slope, and velocity vs. grain size curve. These internal assumptions cannot be modified by the user. *SedSim* determines the venting efficiency iteratively as follows

1. Determine the velocity of the turbidity current in the *i*th iteration.

$$v_i = \left(\frac{8}{f}\frac{\rho_w\ (t) - \rho_w}{\rho_w}\, g\, \frac{Q_{i;}\ (t)}{B} S\right)^{1/3} \qquad \text{(A2.11)}$$

where v is the velocity of the density current (m/s); f is a coefficient that represents the total interfacial frictional effects between the density current and the both the river bed and overlying clear water layer; g is the gravitational constant (9.81 m/s^2); $\rho_{ws}(t)$ is the density of water at 20° C with a suspended solids concentration equal to the concentration of the reservoir's inflow during time period t, $C_{in}(t)$; ρ_w is the density of pure water at 20 °C (zero suspended solids concentration); B is the representative bottom width of the reservoir; S is the representative bed slope of the reservoir; and $Q_{in}(t)$ is the reservoir inflow rate.

Note that the density of water, ρ_{ws}, with suspended sediment concentration C (ppm), was assumed to be given by the following relationship:

$$\rho_{ws} = 0.9982 + 0.0006C \qquad \text{(A2.12)}$$

Eq. (A2.12) was determined using data from *Washburn* [1928], as appears in Table 2.2 below.

Table 2.2. Density of water and sediment mixtures as a function of temperature (°C) and suspended solids concentration (g/L).

Temperature, °C	Pure Water	Water + Sediment *1 g/L*	Water + Sediment *10 g/L*	Water + Sediment *100 g/L*
0	0.999868	1.000491	1.006095	1.062137
4	1.000000	1.000623	1.006226	1.062264
10	0.999728	1.000351	1.005955	1.062002
20	0.998232	0.998855	1.004465	1.060562
30	0.995676	0.996300	1.001919	1.058103

2. Using the velocity, v_i, calculated in Step 1 of iteration *i*, determine the maximum grain size that can be transported by v_i using Figure A2.11 below. This figure represents the relationship between turbidity current velocity and the grain size that can be maintained in suspension [*Fan*, 1996].

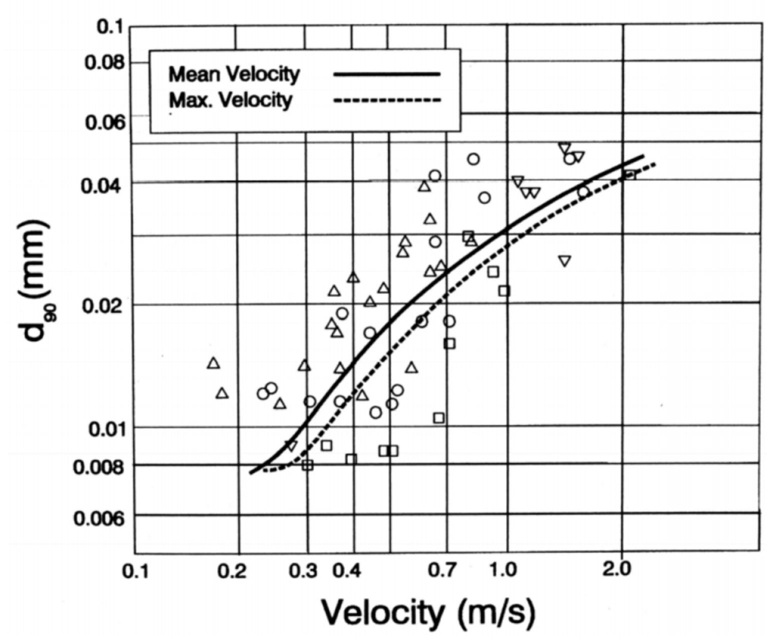


Figure A2.11. Relationship between density current velocity (m/s) and the sediment grain size (mm) that can be maintained in suspension.[12]

The fitted curve appearing in Figure A2.11 representing velocity, *v*, as a function of 90th percentile particle size, d_{90}, can be approximated by the following relationship:

$$d_{90} = -0.0074(v^2) + 0.0369(v) + 0.0007 \quad \text{(A2.13)}$$

3. Remove all grain sizes from suspension that are too large (> d_{90}) to be transported by the velocity of the current, *v*, in iteration *i*.

To complete this step, the following particle size distribution is assumed (Figure A2.12).

[12] Figure taken from *Fan* [1986].

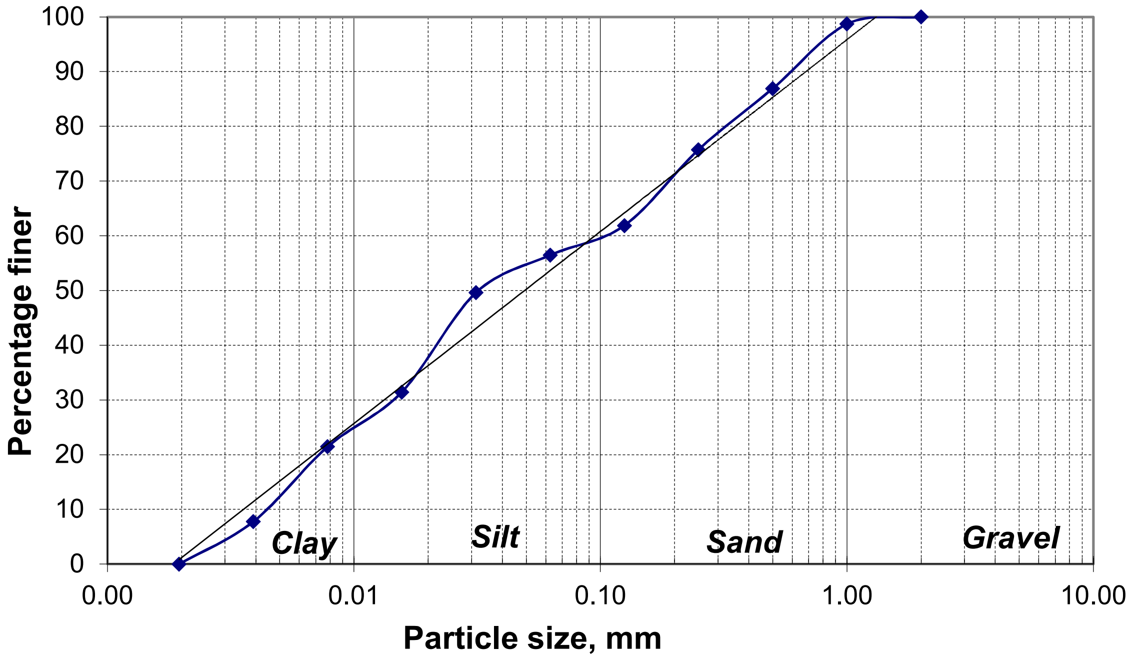


Figure A2.12. Particle size distribution used to compute percent of sediment in suspension that does not settle in the reservoir (is fine enough to be transported by the velocity of the density current).

The following relationship can be used to approximate the data points in Figure A2.12.

$$\% \text{ Finer} = 15.226\ln(d_{90}) + 95.839 \qquad \text{(A2.14)}$$

4. Apply the % finer value determined in iteration step 3 to the concentration of the inflow, and repeat steps 1 - 4 until convergence of the % finer value. The % finer value represents the venting efficiency (%). It is the portion of the inflowing suspended sediment load that can remain in suspension, which is the percentage that can be vented and will not settle. As this %finer value affects water density and thus the velocity of the current, which affects the particle size that can be transported, this iterative process is required.

Once convergence of the % finer value is achieved, the venting efficiency is given by the final % finer value.

If the user chooses to allow density current venting at a particular reservoir, and if the venting efficiency in this table corresponding to the current inflow and concentration exceeds the user-specified minimum venting efficiency (see below), then a percentage of the inflowing concentration equal to the corresponding venting efficiency will be released from the low level gates of the reservoir. The remaining percentage (100-venting efficiency) will settle in the reservoir.

Consider the following example of how the venting efficiency computed in *SedSim* is used:

Average daily flow into reservoir from upstream reach, *Qin*: 100 m^3/s
Average daily concentration into reservoir from upstream reach, *Cin*: 20,000 mg/l
Venting efficiency = *f*(*Qin*, *Cin*) = 30%
Venting flow, *Qout* = *Qin* = 100 m^3/s
Mass released from venting in one day, assuming user defines 30% efficiency as acceptable: 0.3*100 (m^3/s)*20,000 (mg/L)*1000 (L/m^3)*86400 (s/day)*10^{-9} (kg/mg) = 51,840 kg.

In the example above, the sediment concentration released in the vented flow, Q_{vent}, is equal to the product of the sediment concentration in the flow entering the reservoir (from the upstream channel) and the venting efficiency. The venting efficiency is equal to the percentage of sediment remaining in suspension by the time the current reaches the dam

Other sediment removal methods

To account for the removal of sediment from a reservoir in *SedSim*, the following information must be supplied in the "General Sediment Removal" Worksheet by the user for every reservoir in which a sediment removal practice will be simulated:

1. Calendar date on which to begin sediment removal. *Worksheet*: "General Sediment Removal".

2. Removal duration (days). *Worksheet*: "General Sediment Removal".

3. Amount of sediment to be removed (tons). *Worksheet*: "General Sediment Removal".

4. The user-defined name of the system element into which the removed sediment will be distributed. *Worksheet*: "General Sediment Removal".

5. The fraction of sediment that is removed from the active storage zone (the remainder of sediment is assumed to be removed from the dead storage zone). *Worksheet*: "General Sediment Removal".

For these techniques, the *SedSim* model approach is very simple. On the date on which the user specifies sediment removal is to be initiated, the model attempts to remove the user-specified amount of sediment volume from the reservoir, while first making sure that no more sediment than is initially available can be removed from the reservoir. The volume removed may be distributed over a user-specified number of days, and is transferred to the settled sediment reserve at a location in the modeled system that the user must specify. If no destination location for the sediment is specified, the sediment is assumed to permanently leave the modeled system. The user can optionally specify the fraction of sediment volume removed that contributes to recovery of active storage, while the remainder of storage is assumed to be recovered in the dead storage zone. Hydropower production and reservoir storages/releases are not altered during the removal process.

3 Getting Started

The following section discusses system requirements for running the *SedSim* model, and also offers a quick start guide. This guide briefly describes the steps that are necessary in Excel to run the *SedSim* model. More detailed information is provided in later sections of this documentation, especially regarding the preparation of input data to the model.

System Specifications

For best performance, the *SedSim* model should be run using MS Excel 2007 or newer (i.e., Excel 2010). Depending on the size of the model you build, earlier versions of Excel (e.g., Excel 2003) have stricter limitations on the maximum RAM that can be used, and may result in an inability to run the model due to memory usage errors. The model does not require a fast processor to operate, but a large model (many system elements and/or long time series) can require extensive memory usage. In general, 2 GB of RAM should be suitable for most applications of this model.

Quick-Start Guide

1. **Open up the main (macro) workbook.**

   Open the main *SedSim* model file. This file will be referred to as "SedSim_Model.xlsm" throughout this documentation for convenience, but the file can be given any name by simply right-clicking on the file icon when the file is closed and selecting "rename".

   Upon opening the workbooks, you may be asked if you wish to enable macros. Click the "Enable Macros" option to allow the sediment model to execute properly.

   Enable macros in security settings. To be certain that the *SedSim* model will always run on your computer, in the "SedSim_Model.xlsm" workbook, in Excel 2007 (or Excel 2010), go to File (or MS Office Button) → Options → Trust Center→Trust Center Settings→Macro Settings →Enable All Macros. When you are finished running the model in Excel, these settings should be returned to their original status to avoid potential security threats to your computer. Alternatively, as described in step 1 above, your version of Excel may provide a warning message when you first open the *SedSim* model that asks if you wish to enable the currently open *SedSim* model Excel file to be run on your computer, among other Macro options. You can enable the model to be run on your computer this way as well.

   Figure A3.1 shows the interface associated with the main workbook of the *SedSim* model. It is designed to be generic so it can be used without code modification to run any input file.

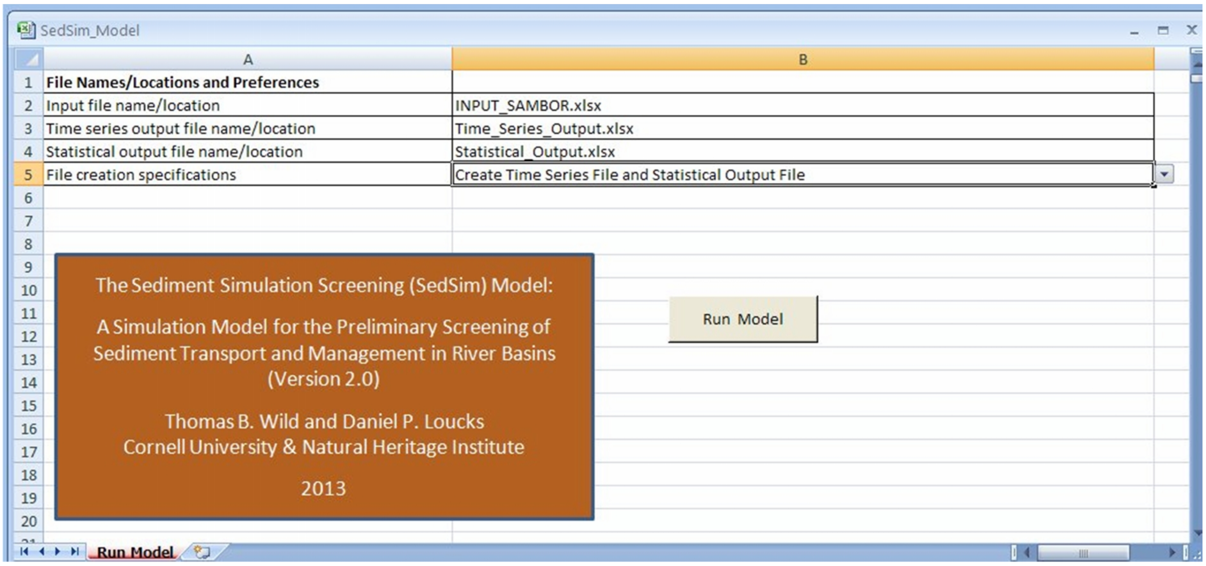


Figure A3.1. Interface for the *SedSim* model. It ("SedSim_Model.xlsm" workbook) has only one worksheet. Clicking on the right hand box of line (row) 5 results in the arrow shown at the far right of line 5. Clicking on the arrow will show options available for line 5, any of which can be selected.

2. **Load in the input data and specify assumptions.**

   Place all relevant time series output from a hydrologic model in the worksheets within the "SedSim_INPUT.xlsx" files. All colored worksheets will require some input, whereas un-colored worksheets will not require user input and are instead populated during the execution of the macro. Model-related assumptions (e.g., sediment density) can be modified in the "Simulation Specifications" worksheet of the input data workbook.

   The "SedSim_Model.xlsm" workbook is the only one that is required to be open for the simulation to run properly. The Input file and output file do not need to be opened beforehand. The input file will be opened and closed automatically when needed by the main macro, and the output file is automatically created, saved and closed by the main macro.

3. **Run the model.**

   This can be performed by clicking the "Run Model" button in the "SedSim_Model.xlsm" workbook. (See Fig 3.1). During the execution of the model, the model will automatically close the input data file. The model was designed to automatically close the input data file once all data have been imported into internal arrays because keeping the input file open can exhaust the maximum memory usage limits of Excel for a large reach/reservoir network or long simulation duration. The model may produce two different types of error messages during execution: (1) a detailed error message generated by *SedSim* that the user must acknowledge, by clicking "OK" on the automatically generated error message box, before the simulation can proceed; and (2) an excel VBA error message, which is not likely to contain detailed instructions, and which is likely the result of improper input data specification or input/output file naming.

Note: If the model will not run and displays an error regarding the Microsoft Excel “Solver” package, you may need to install a reference to “Solver” in the VBA code. Do this by opening up the "SedSim_Model.xlsm" and accessing the VBA code by selecting Alt+F11 on the keyboard. Within the “Project” menu on the left hand side of the screen, click on the main model file to reveal its sub-menu, then double click the “SedSim_Model” module within the sub-menu. In the main menu at the top of the screen, select Tools-->References. Find and check the “Solver” box. Click OK to install the solver references. Re-run the model to see if this change permits the model to run.

4. Evaluate results.

The results of the simulation run are contained in the “SedSim_OUTPUT.xlsx” file. Are these results reasonable given the input data? One approach to gain confidence in the results is to create input data for relatively simple systems that should lead to obvious results, and then see if indeed they did.

4 Overview of Model File Structure

The *SedSim* model consists of three different types of Excel workbooks (as summarized in Figure A4.1 below):

1. A data input file (e.g., "SedSim_INPUT.xlsx"),
2. The main model file (e.g., "SedSim_Model.xlsm"), and
3. Output file(s) (e.g., "SedSim_OUTPUT.xlsx").

Users can name these files as they wish. For example, the input file for the single reservoir simulation used in this manual could be "Sambor_Input.xlsx" or "INPUT_SAMBOR.xlsx".

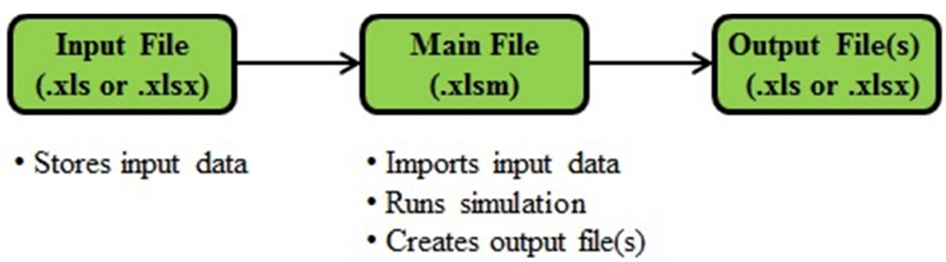


Figure A4.1. Schematic of data flow in the *SedSim* model.

From this point forward, excel files (e.g., "SedSim_INPUT.xlsx") will be referred to as *workbooks*, whereas the tabs within the workbooks will be referred to as *worksheets*. While the three files in the list above are given names (e.g., "SedSim_INPUT.xlsx"), the user will control the naming of all workbooks in their application of the *SedSim* model. Referring throughout this manual to the files by the names in the list above (e.g., "SedSim_INPUT.xlsx") is only done for convenience.

For the model to run properly, only the main model file ("SedSim_Model.xlsm") must be open. The location of the files does not affect the ability of the model to execute properly as long as the file locations are all properly specified in the "SedSim_Model.xlsm" file. However the time required to load the data, run the model and save the results may be faster if the files are located on the computer's hard drive, rather than on an external hard drive or flash drive.

A description of the three primary file types (main file, input file and output files) is provided in Chapters 5, 6 and 7, respectively. The discussion will focus on the purpose of each workbook and the actions a user must take to properly prepare each worksheet within each workbook.

5 Main Model File Description

The main model file ("SedSim_Model.xlsm") has two primary purposes:

(1) It contains the Excel VBA code needed for simulation and permits its execution by clicking on the “Run Model’ button, and
(2) It contains an interface into which users are required to specify the names and directory locations of input and output files, as well as which output files the user wants the model to create. See Figure A3.1.

While this file is referred to here as "SedSim_Model.xlsm", the user can specify any name for this file (e.g., "ModelFile.xlsm"), as long as the ".xlsm" extension is maintained. To run the model, after providing all required inputs click on the "Run SedSim Model" button located within the worksheet titled "Run Model". (Note: the name of the main worksheet within this workbook must remain "Run Model", or the model will not execute). During the execution of the simulation run, the model will attempt to automatically close the “SedSim_INPUT.xlsx” file because the data will no longer be needed.

If your model input and output files are particularly large, you may wish to increase the “Auto save” time increment under File → Excel Options. This will avoid long auto-save delays. You can customize the auto-save time to a particular workbook so that standard auto-save settings are still maintained for other workbooks not related to the sediment model.

<u>Files Names/Locations and Preferences.</u>

a) **Input File name/location.** Specify the location and file name of the input file on the computer. For example, the following would be a valid file name and location: C:\Users\YourName\My Documents\SedSim_INPUT.xlsx. The model will use this information to locate, open and import input data from the specified file. The file can be located anywhere on the computer, but the file name must have a .xlsx or .xls extension. (If this file is to be located in the same directory as the main model workbook, only a file name must be specified, without any file routing information. If no file routing or name is specified, the model will assume the input file is located in the same directory as the main model workbook, and is named "Input.xlsx").

b) **Time series output file name/location.** Specify the desired location and file name of the time series output file that will be automatically created and saved by the model, assuming the user chooses to have this file created (see the "File creation specifications" options below). For example, the following would be a valid file name and location: C:\Users\YourName\My Documents\Time_Series_Output.xlsx. The model will use this information to create and save the specified file, and export data to this file. The file can be located anywhere on the computer, but the file name must have a .xlsx or .xls extension and must not have the same name as pre-existing files in the specified location or the pre-existing files will be replaced. (If this file is to be located in the same directory as the main model workbook, only a file name must be specified, without any file routing information. If no file routing or name are specified, the model will assume the time series output file should be located in the same directory as the main model workbook, and will be named "Output_Time_Series.xlsx".).

c) **Statistical output file name/location.** Specify the desired location and file name of the statistical summary output file that will be automatically created and saved by the model, assuming the user chooses to have this file created (see the "File creation specifications" options below). For example, the following would be a valid file name and location: C:\Users\YourName\My Documents\Statistical_Output.xlsx. The model will use this information to create and save the specified file, and export data to this file. The file can be located anywhere on the computer, but the file name must have a .xlsx or .xls extension and must not have the same name as pre-existing files in the specified location or the pre-existing files will be replaced. (If this file is to be located in the same directory as the main model workbook, only a file name must be specified, without any file routing information. If no file routing or name are specified, the model will assume the statistics output file should be located in the same directory as the main model workbook, and will be named "Output_Statistics.xlsx".).

d) **File creation specifications.** Select one of the following options from the drop-down menu:

i. Create only Time Series Output File
ii. Create only Statistical Output File
iii. Create Time Series File and Statistical Output File

These four options allow the user to specify as many, or as few, output data files as wanted. These options are available because the output files, depending on their size, can take significant time and storage space to be created, populated with data, and saved.

6 Input Model File Description

Overview of Input Workbook

To illustrate how *SedSim* works a simple single reservoir problem will be simulated. The simplified example will be based on the proposed Sambor reservoir in the Mekong River.

The input workbook file, "INPUT_SAMBOR.xlsx," to the *SedSim* model consists of a variety of separate worksheets, each responsible for storing a different type of information. This file should be updated, saved and closed before the simulation is conducted. The simulation will run if the file is open at the start of simulation, but this may make the simulation proceed more slowly (or fail to execute) if your RAM is sufficiently low given the duration of simulation and number of system elements being simulated.

Some of the worksheets in this workbook are required to contain time series. For such cases, additional discussion about formatting of the input data is provided below.

In time series worksheets, each column represents a unique location in the modeled system, whereas each row represents a date. Time series should begin in the second column on the second row, as the first column should just contain dates (in DD/MM/YYYY format).

The name of the location for which each time series applies must be listed in the first row of the associated column. The name of the location must *contain* the same exact name as is listed in the "Network Connectivity" worksheet for that reservoir. For example, if a reservoir in the system is defined in the network connectivity matrix as "LowerSeSan3", then the string typed into the third row for a particular column must contain the letters "LowerSeSan3" in that exact order. There are no case restrictions in this regard; that is, "LoWeRsEsAn3" would also suffice, as would "LoWeRsEsAn3-POOL", because the correct name is still contained within the string, even though the word POOL is added. However, "LoWeR sE sAn 3-POOL" would not suffice as a time series column heading, because spaces are placed in locations in which they did not appear in the name of the reservoir in the "Network connectivity" worksheet.

For each variable for which you are providing time series input, there is no limit to the number of contiguous columns or rows for which data can be provided. The model will search for the time series data for each element by name (located at the top of each time series) for the dates contained within the simulation horizon, and will thus skip data that do not pertain to elements and dates being modeled in the current simulation. This is especially useful for cases in which simulations corresponding to different levels of development (e.g., different numbers of reservoirs) or different time horizons in the basin are of interest. This is because one large data set can be stored in the input file corresponding to the maximum extent of development, and simulations with fewer reservoirs will not then require new, smaller input files to be created. This being said, changes to time series files can still be required when a new system configuration or time horizon is simulated. For example, do not store incremental flow data in the "Incremental Flow" worksheet for junctions that exist in the modeled system but at which incremental flows do not occur in the current simulation.

The date on which each time series value occurs must appear in the first column on the same row on which the associated time series value occurs. If no data exist for a particular element, then no data are required to be entered for that element. For example, if one worksheet corresponds to reservoir evaporation, then if the system has 41 reservoirs but evaporation time series for only 40 of them are available, then the worksheet only needs 40 time series columns. If you omit the time series input for a particular system element (or if you incorrectly spell the name of the element in the column heading), the model will assume all zero values for the omitted element. However, the model will automatically generate a warning message (before simulation proceeds) that indicates you have omitted data, and for what element. (No such error messages will be generated for any incremental flow data supplied by the user in the "Incremental Flow" worksheet). The time series columns can be placed in any order in the worksheet, as long as the reservoir's name is correctly spelled in the third row of the time series column, as explained above.

No row gaps or column gaps in time series data are permitted. That is, the *SedSim* model assumes data are provided for every day of simulation, and that time series are stacked as contiguous columns. For example, there should not be a sequence of two numbers in the time series that skips a date, nor should there be any blank rows or columns.

Note that some of the conditions discussed above for time series worksheets also hold for worksheets that do not require time series input. For example, no gaps between columns or rows should exist in any of the input data worksheets. Additionally, data for more than one element can be provided, as the model will locate and import only data pertaining to elements that will be included in the simulation.

The following worksheets are required at a minimum to conduct a simulation:

A. Simulation Specifications
B. Network Connectivity
C. Sediment Loads
D. E-V-A-S
E. Storage Volume Target OR Storage Volume Elevation Target (depending on preferences established in "Reservoir Specifications" worksheet)
F. Incremental Flows
G. Evaporation Data
H. Environmental Flow Data
I. Reach Specifications
J. Reservoir Specifications
K. Flushing (only if Flushing will be simulated as specified in "Reservoir Specifications" worksheet)
L. Sluicing (only if Sluicing will be simulated as specified in "Reservoir Specifications" worksheet)

M. Density Current Venting (only if Density Current Venting will be simulated as specified in "Reservoir Specifications" worksheet)
N. Bypassing (only if Bypassing will be simulated as specified in "Reservoir Specifications" worksheet)
O. General Sediment Removal (only if General Sediment Removal will be simulated as specified in "Reservoir Specifications" worksheet)
P. Outlet Capacity Data

Description of Each Worksheet

1. System Schematic and Meta File

In this worksheet, users are encouraged to place a map (or schematic) of the system being modeled. Any figures or data placed in this worksheet will not be used in the execution of the sediment model. Meta data pertaining to the model inputs and assumptions can also be included in this worksheet. An example of this worksheet is shown below.

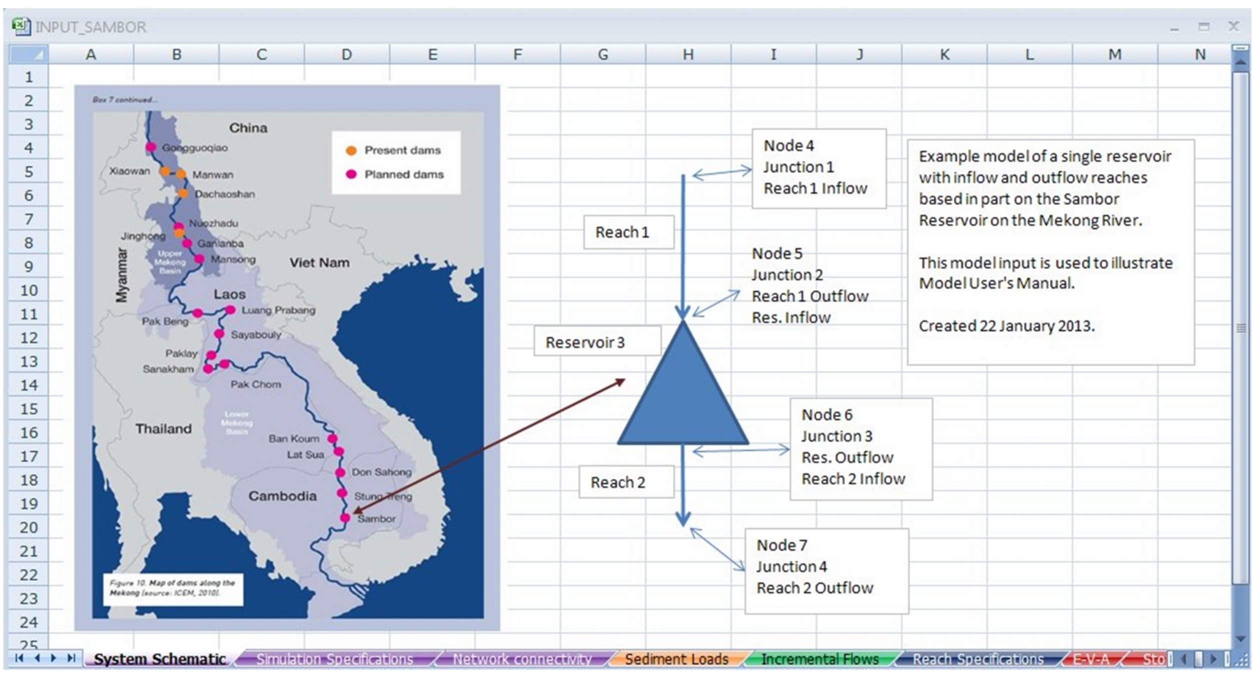
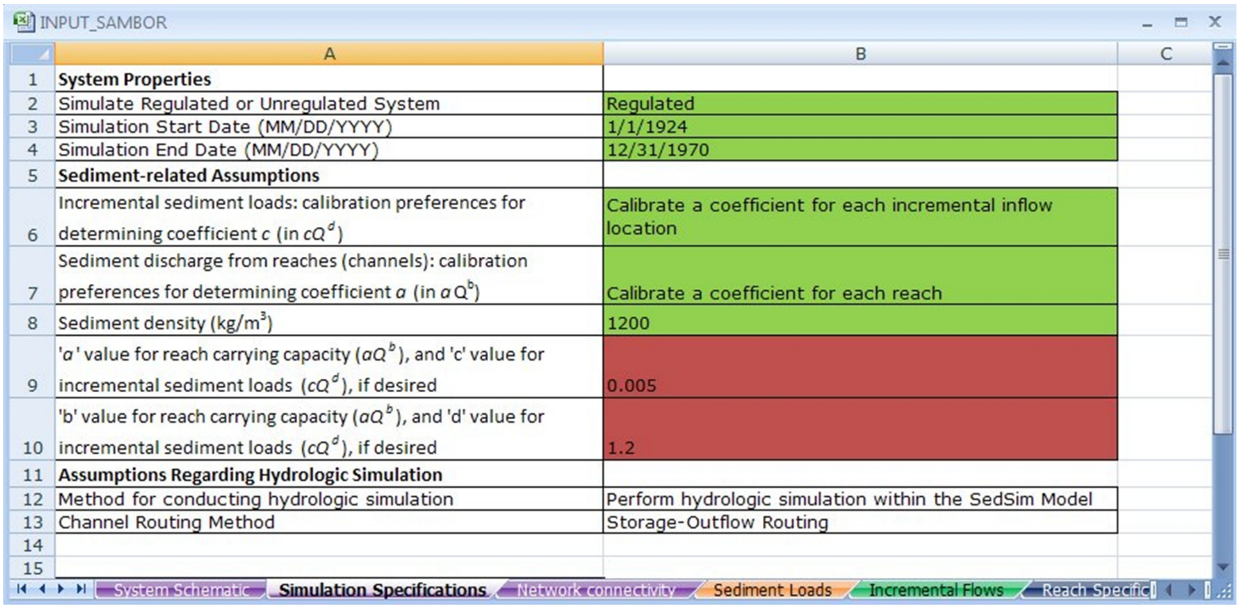


Figure A6.1. Illustration of a Map and Meta data on the “System Schematic” worksheet page of Input file “INPUT_SAMBOR.xlsx”.

This worksheet is accessed by clicking on the purple “System Schematic” worksheet tab at the bottom of the worksheet. Nothing in this worksheet is used during the simulation.

2. Simulation Parameters and Specifications

This worksheet is shown below. It is accessed by clicking on the "Simulation Specifications" worksheet tab at the bottom of the input data workbook.


INPUT_SAMBOR

	A	B	C
1	**System Properties**		
2	Simulate Regulated or Unregulated System	Regulated	
3	Simulation Start Date (MM/DD/YYYY)	1/1/1924	
4	Simulation End Date (MM/DD/YYYY)	12/31/1970	
5	**Sediment-related Assumptions**		
6	Incremental sediment loads: calibration preferences for determining coefficient c (in cQ^d)	Calibrate a coefficient for each incremental inflow location	
7	Sediment discharge from reaches (channels): calibration preferences for determining coefficient a (in aQ^b)	Calibrate a coefficient for each reach	
8	Sediment density (kg/m^3)	1200	
9	'a' value for reach carrying capacity (aQ^b), and 'c' value for incremental sediment loads (cQ^d), if desired	0.005	
10	'b' value for reach carrying capacity (aQ^b), and 'd' value for incremental sediment loads (cQ^d), if desired	1.2	
11	**Assumptions Regarding Hydrologic Simulation**		
12	Method for conducting hydrologic simulation	Perform hydrologic simulation within the SedSim Model	
13	Channel Routing Method	Storage-Outflow Routing	
14			
15			

System Schematic | Simulation Specifications | Network connectivity | Sediment Loads | Incremental Flows | Reach Specific

Figure A6.2. The "Simulation Specifications" worksheet of the input file for the *SedSim* model.

In this worksheet, users are required to enter a variety of assumptions for the model to use during the simulation run. Any cell highlighted in green requires input from the user, whereas any cell highlighted in red only requires user input if the model feature pertaining to the cell will be used. Do not leave blank any cells that are highlighted green. Also, do not change the location of any data descriptions within the workbook, as the model assumes that all parameters will be located in particular, pre-established cells.

System Properties Category

The following information must be specified by the user in this section:

a) **Regulated or unregulated simulation.** Select either "Regulated" or "Unregulated" from the drop-down menu. The regulated system is defined as one in which reservoirs and diversions are present, with the number and connectivity of reservoirs and diversions, and the system flows that have been affected by these structures, are specified in the input data. The unregulated simulation simply assumes that no reservoirs or diversions exist, and therefore all locations at which reservoirs are expected to exist (or currently exist) become reaches. This option is not necessarily the same as simulating the "current" state of an already regulated basin.

b) **Simulation start and end dates.** Specify the simulation start date and end dates in MM/DD/YYYY format. In the model input files, several time series inputs for each system location (and several variables) may be required, so users should be careful to specify start and end dates of simulation for which a corresponding value exists for every variable of input time series data.

Sediment-related Assumptions Category

c) **Incremental sediment loads: calibration preferences for determining coefficient *c* (in sediment rating curve equation (cQ^d) for each incremental inflow location *i*.** Select one of the following options from the drop-down menu:

   i. Calibrate a coefficient for each incremental inflow location.
   ii. Use coefficients calibrated in most recent simulation.
   iii. Specify one coefficient for all incremental flow locations.
   iv. Specify a separate coefficient and exponent for each incremental inflow location.

A few comments about these options are now important to make, but note that detailed discussion of the calibration process is available in Chapter 2 under the *SedSim Model Development* section.

Option 1 results in a series of calibrations to determine an appropriate *c* value for every location in the system at which an incremental flow (and therefore sediment load occurs). This requires that the model calls Microsoft Excel's Solver to calibrate a parameter for each location. The model will store and save the calibrated parameters in the output files.

Option 2 allows the user to save time and CPU usage by running a simulation using incremental sediment load parameters that were determined in a previous calibration run. If you have selected Option 1 in a previous simulation run, the model will store and save the calibrated parameters in the input data file used to supply data for that simulation run. Selecting Option 2 will mean the model imports those most recently calibrated incremental sediment load parameters stored in the current input data file.

Option 3 allows the user to specify one set of two parameters (the same coefficient and exponent to be used at all incremental inflow locations for sediment load generation). This is a useful option for studies with very limited data availability. For example, there may not be enough evidence that having different parameters at different locations in the system is reasonable. The two values should be specified in the "Simulation_Specifications" worksheet in the two cells highlighted in red, as described below. The two cells are highlighted in red, rather than green, because these specifications are only required if Option 3 is selected.

Option 4 allows the user to specify a different set of two parameters (coefficient and exponent) to be used for sediment load generation at each incremental inflow location. As the model will not perform a calibration to determine these values, the values must be supplied by the user in the "Annual_Sed_Loads" worksheet. The "Annual_Sed_Loads" worksheet stores mean annual sediment loads for each incremental inflow location. Thus, additional columns are available for also storing coefficients and exponents to be used for generating incremental sediment loads.

Note that, depending on the watershed in which this model is applied, you may wish to establish the parameters ‘c’ and ‘d’ so that proportionally more sediment is transported during higher discharge events, as is often observed in practice [*Walling*, 2009].

d) **Sediment discharge from reaches (channels): calibration preferences for determining coefficient a (in sediment rating curve equation aQ^b).** Select one of the following options from the drop-down menu:

   i. Calibrate a coefficient for each reach.
   ii. Use coefficients calibrated in most recent simulation.
   iii. Specify one coefficient for all reaches.
   iv. Specify a separate coefficient and exponent for each reach.
   v. Sediment mass out (kg) = Sediment mass in (kg).

A few comments about these options are now important to make, but note that detailed discussion of the calibration process is available in Chapter 2 under the *SedSim Model Development* section.

Option 1 results in a series of calibration to determine an appropriate *a* value for the sediment carrying capacity function for every reach (channel) in the system. This requires that the model calls Microsoft Excel's Solver to calibrate a parameter for each reach, which can take a significant amount of time depending on the number of locations and simulation duration. The model will store and save the calibrated parameters in the input data file used to supply data for the simulation run

Option 2 allows the user to save time and CPU usage by running a simulation using reach sediment carrying capacity parameters that were determined in a previous calibration run. If you have selected Option 1 in a previous simulation run, the model will store and save the calibrated parameters in the input data file used to supply data for that simulation run. Selecting Option 2 will mean the model imports those most recently calibrated reach carrying capacity parameters stored in the current input data file.

Option 3 allows the user to specify one set of two parameters (coefficient and exponent) to be used in the sediment carrying capacity function for all reaches in the system. These two values should be specified in the "Simulation_Specifications" worksheet in the two cells highlighted in red, as shown in Figure A6.2. The two cells are highlighted in red because these specifications are only required if Option 3 is selected.

Option 4 allows the user to specify a different set of two parameters (coefficient and exponent) to be used in the sediment carrying capacity function for each reach. As the model will not perform a calibration to determine these values, the values must be supplied by the user in the "Reach_Data" worksheet.

Option 5 allows the user to assume that each reach maintains a sediment transport capacity that results in a daily discharge of sediment from each reach that is equal to the sediment inflow to the reach, regardless of the water inflow and outflow rates. This is a steady state assumption, in that the sediment leaving the system every day should equal the sum of the sediment incrementally generated within the system every day. This is not a physically realistic assumption, but can be useful for evaluating the impact of assumptions regarding sediment transport capacity in studies in which very little is known about sediment production in channels.

Note that, depending on the watershed in which this model is applied, you may wish to establish the parameters "a" and "b" so that proportionally more sediment is transported during higher discharge events, as is often observed in practice [*Walling*, 2009].

e) **Sediment density.** Specify one value for sediment density (kg/m^3). This value is only used to determine the volume (m^3) of sediment settles in each reservoir in each day, given a mass (kg) of settled sediment.

f) **The "a" value for all reach carrying capacities (aQ^b), and 'c' value for all incremental sediment loads (cQ^d), if desired.** A value must be specified here only if option 3 is selected in either the Incremental Sediment Load category ("Specify one coefficient for all incremental flow locations") or the reach carrying capacity category ("Specify one coefficient for all reaches").

g) **The "b" value for all reach carrying capacities (aQ^b), and 'd' value for all incremental sediment loads (cQ^d), if desired.** The value in this cell is jointly imported by the incremental sediment load generation function and by the reach carrying capacity function to be used as the exponent in each case. The only reason not to specify a value in this cell is if either (1) all of the calibrated parameter values from a previous simulation are to be used, or (2) appropriate options have been selected in order for the user to specify exponent values for each location in separate worksheets (the "Annual_Sed_Loads" worksheet for the incremental sediment load function, and the "Reach_Specifications" worksheet for the reach carrying capacity function).

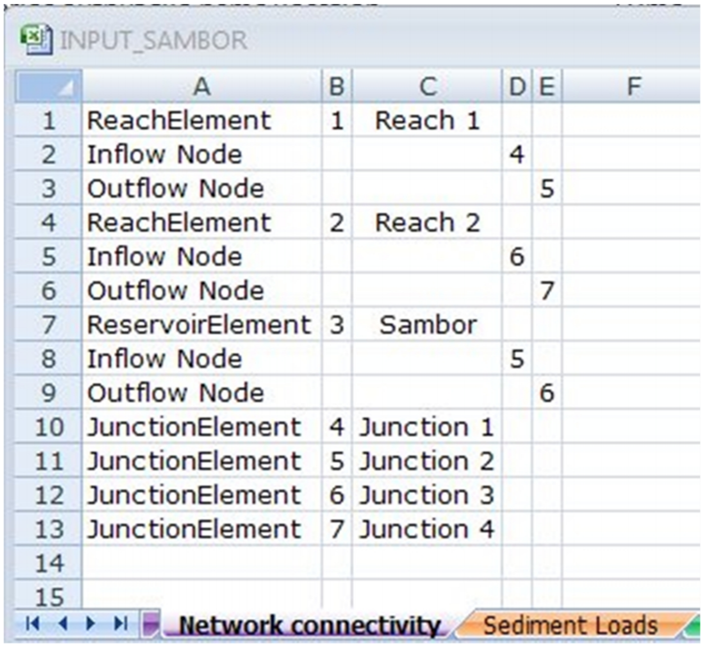
h) **Channel Routing Method.** Select one of the following options from the drop-down menu:

   i. Storage-Outflow Routing
   ii. Null Routing (Flow in = Flow out)

Storage-outflow routing determines daily reach outflow rates (m^3/s) as a function of reach storage (m^3). This option is described in Chapter 11. Null routing results in reach inflow rate equal to reach outflow rate (a steady state assumption).

3. Network connectivity

The "Network connectivity" worksheet contains the network connectivity matrix, which describes how system elements (reaches, reservoirs, junctions, and diversions) are connected together.



INPUT_SAMBOR

	A	B	C	D	E	F
1	ReachElement	1	Reach 1			
2	Inflow Node			4		
3	Outflow Node				5	
4	ReachElement	2	Reach 2			
5	Inflow Node			6		
6	Outflow Node				7	
7	ReservoirElement	3	Sambor			
8	Inflow Node			5		
9	Outflow Node				6	
10	JunctionElement	4	Junction 1			
11	JunctionElement	5	Junction 2			
12	JunctionElement	6	Junction 3			
13	JunctionElement	7	Junction 4			
14						
15						

Figure A6.3. Portion of "Network connectivity" worksheet of input file containing network configuration of the system being simulated.

The "Network connectivity" worksheet is used to assign unique names, ID numbers, and element types to every system element, and to describe to which junctions the upstream and downstream ends of each reach, reservoir and diversion are connected. Column A contains the element name and column B the element number. Column C is the element name used in the simulation, and columns D and E are the inflow and outflow nodes associated with a particular reach or reservoir element. Nodes are also called junctions.

The network connectivity matrix must be 5 columns wide. Every element that exists in the modeled system, which includes reaches, reservoirs, junctions and diversions, must be represented in at least one row of the network connectivity matrix. The process is different depending on what type of element is of concern. Each will be addressed separately below.

The following describes what users should type into each specified cell. The string enclosed in quotes should be entered into the specified cell without including the quotation marks. Follow very closely the syntax suggested below. For example, when establishing a reach element, the single string "ReachElement" must be typed in the first column, not the two strings "Reach Element". Note that reaches must have a single inflow node and a single outflow node to be modeled properly in the *SedSim* model. Conversely, reservoirs can have multiple inflow nodes. For reaches and reservoirs, users should follow the steps described below to (1) establish the existence of the element, and (2) define its inflow and outflow nodes (inflow nodes must appear first, and outflow nodes must appear second). Names and ID numbers must be unique for every system element. No element should ever be defined with an ID of "0".

<u>Reaches:</u>

Row 1 [required; used to establish existence of element, its ID, and its name)]
- Column 1: "ReachElement"
- Column 2: "Unique Reach ID #" (e.g., 105)
- Column 3: "Unique Reach Name" (e.g., 12008)
- Column 4: No input required
- Column 5: No input required

Row 2 [required; used to establish the inflow node for the reach and the ID of that inflow node]
- Column 1: "Inflow Node"
- Column 2: No input required
- Column 3: No input required
- Column 4: "Unique ID of the Inflow Junction; must be the same ID that is established when the node/Junction is defined"
- Column 5: No input required

Row 3 [required; used to establish the outflow node for the reach and the ID of that outflow node]
- Column 1: "Outflow Node"
- Column 2: No input required
- Column 3: No input required
- Column 4: No input required
- Column 5: "Unique ID of the Outflow Junction; must be the same ID that is established when the node/Junction is defined"

<u>Reservoirs:</u>

Row 1 [required; used to establish existence of Reservoir, its ID, and its name)]
- Column 1: "ReservoirElement"
- Column 2: "Unique Reservoir ID #" (e.g., 105)
- Column 3: "Unique Reservoir Name" (e.g., V009-Buon Tua Srah)
- Column 4: No input required
- Column 5: No input required

Row 2 [required; used to establish the first inflow node for the Reservoir and the ID of that inflow node]
- Column 1: "Inflow Node"
- Column 2: No input required
- Column 3: No input required
- Column 4: "Unique ID of the first Inflow Junction; must be the same ID that is established when the node/Junction is defined"
- Column 5: No input required

Row 3 [optional; used to establish the second inflow node for the Reservoir and the ID of that inflow node]
- Column 1: "Inflow Node"

Column 2: No input required
Column 3: No input required
Column 4: "Unique ID of the second Inflow Junction, established when defining the Junction"
Column 5: No input required

Row 4 [required; used to establish the outflow node for the Reservoir and the ID of that inflow node]
Column 1: "Outflow Node"
Column 2: No input required
Column 3: No input required
Column 4: No input required
Column 5: "Unique ID of the Outflow Node, established when defining the Junction"

Junctions:

Row 1 [required; used to establish the existence of a Junction node]
Column 1: "JunctionElement"
Column 2: "Unique Junction ID #" (e.g., 2675)
Column 3: "Unique Junction Name" (e.g., Junction 10)
Column 4: No input required
Column 5: No input required

Diversions:

Row 1 [required; used to establish the existence of the Diversion, and the reservoir at which it originates]
Column 1: "DivertedOutletElement"
Column 2: "Unique Diversion ID #" (e.g., 1385)
Column 3: No input required
Column 4: No input required
Column 5: "Name of Reservoir at which diversion originates, same as listed when initially establishing reservoir."

Row 2 [required; used to establish the ID of the junction node to which the diversion flows]
Column 1: "Outflow Node"
Column 2: No input required
Column 3: No input required
Column 4: No input required
Column 5: "Unique ID# of Junction to which diversion flows"

4. Sediment Loads

The "Sediment Loads" worksheet contains estimates of the cumulative average annual sediment loads (in kg/yr) that are discharged past every location in the system at which incremental flows enter. See Figure A6.4 below.

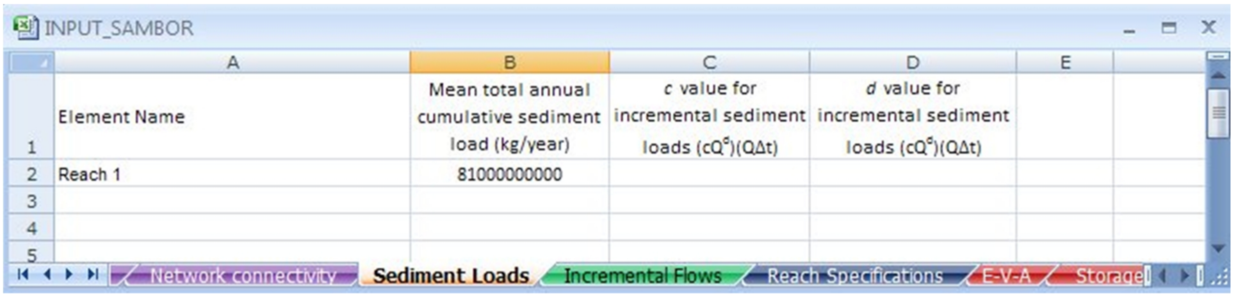


Figure A6.4. "Sediment Loads" worksheet of the input file.

This worksheet should contain four columns. In the first column, each row should contain sediment load data relevant to each system element (reach or reservoir) into which incremental sediment loads (and incremental flows) will enter the system at an upstream inflow junction of the element. Data entry for the first element should begin on the second row. The reservoir or reach name in each row of the first column must be identical to the name as defined in the "Network connectivity" worksheet in the input file. Data for more locations than just those being modeled can be stored in this worksheet, as the model will only import information relevant to elements being simulated. Each column represents a different input data requirement. Column data entries should begin on the second column.

a) **Mean total annual cumulative sediment load (kg/year).** In column 2, users should enter the mean annual cumulative sediment yield (kg/km^2-yr) that is expected to flow into each incremental inflow location in a completely unregulated system. This should be the mean annual sediment load that is discharged past each reservoir site, assuming no reservoirs exist in the system to trap sediment, and assuming that the system is in relative balance. Assuming the system is in balance requires that there are no long-term sediment sinks. All sediment generated upstream of an incremental inflow location is expected to be discharged past the incremental inflow location, on average, when the system is in balance). The model will only import this value for calibration purposes (calibrating c and d in Eq. (A2.2)). Thus, this column is only required if the user selects the option to calibrate a coefficient for each incremental inflow location in the "Simulation Specifications" worksheet of the input workbook.

b) **The *c* value for incremental sediment load generation, Eq. (A2.2).** In column 3, specify a coefficient value to be used by the model directly in Eq. (A2.2). This column is only required if the user chooses not to conduct a calibration of incremental sediment load coefficients using the model, and instead prefers to supply the model directly with these coefficient values. The preference to supply these values instead of conducting a calibration must be established in the "Simulation Specifications" worksheet of the input workbook.

c) **The *d* value for incremental sediment load generation, Eq. (A2.2).** In column 4, specify an exponent value to be used by the model directly in Eq. (A2.2). This column is only required if the user chooses not to conduct a calibration of incremental sediment load coefficients using the model, and instead prefers to supply the model directly with these exponent values. The preference to supply these values instead of conducting a calibration must be established in the "Simulation Specifications" worksheet of the input workbook.

5. Incremental Flows

The “Incremental Flows” worksheet, shown in Figure A6.5, defines where the incremental flows take place and when.

INPUT_SAMBOR

	A	B	C	D
1	Date	Junction 1		
2	1/1/1924	4132		
3	1/2/1924	4220		
4	1/3/1924	4018		
5	1/4/1924	4271		
6	1/5/1924	4232		
7	1/6/1924	4219		
8	1/7/1924	4219		
9	1/8/1924	4142		
10	1/9/1924	6545		
11	1/10/1924	8855		
12	1/11/1924	8902		
13	1/12/1924	4612		
14	1/13/1924	4502		
15	1/14/1924	4501		
16	1/15/1924	4360		

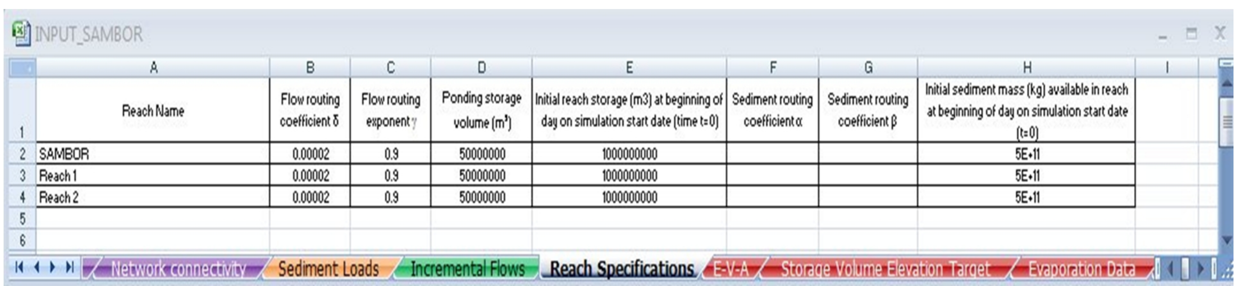
Incremental Flows | Reach Specifications

Figure A6.5. Portion of the “Incremental Flows” worksheet of the input file. In this example these are the flows that enter the upstream reach of the reservoir, Junctrion 4, and get routed through the reach and enter the reservoir.

The sheet is only required to contain average daily incremental flow rates (m^3/s) that enter each junction in the modeled system. Incremental flows should only include those flows that locally enter the modeled system, rather than flows that have already entered the system upstream. Each column should represent a time series of incremental flow rates that enter a particular junction, whereas each row represents the incremental flow rates for all junctions for a particular date. As with all other time series sheets, time series data should begin on the second column and second row, dates should begin on the first column and second row, and the reservoir name should be placed on the first row of every time series column (beginning with the second column). The junction name in each column must be identical to the junction's name as defined in the "Network connectivity" worksheet in the input file. Time series data for more than just those junctions for which elevation targets will apply can be stored in the worksheet, as can data for more dates than just those contained within the simulation horizon. The model will locate and import only the data necessary to conduct the simulation. However, be careful not to store incremental flow data in this worksheet for junctions that exist in the modeled system but at which incremental flows do not occur in the current simulation.

6. Reach Specifications

"Reach Specifications" worksheet stores all data relevant to sediment transport and flow routing in river reaches (channels). Each row corresponds to a different reach in the modeled system for which data exist. The reach name stored in each row must be identical to the reach name as defined in the "Network connectivity" worksheet in the input file. Each column in this worksheet corresponds to a different category of information for which the user should supply data for all reaches for which the data category is relevant. (Each of these categories is introduced in detail below). If all data columns do not apply to a particular reach, no row for the reach is needed. Do not rearrange the locations of columns, as the model searches in specific columns for specific information. Importantly, the model converts reservoirs to reaches when the user runs an unregulated simulation. Thus, each reservoir that will exist in the regulated system simulation should be listed in a separate row in this worksheet (in addition to all reaches that will exist in the regulated system). The data you specify in each column on the row corresponding to each reservoir name will only be applied to the unregulated simulation.



INPUT_SAMBOR

Reach Name	Flow routing coefficient δ	Flow routing exponent γ	Ponding storage volume (m³)	Initial reach storage (m3) at beginning of day on simulation start date (time t=0)	Sediment routing coefficient α	Sediment routing coefficient β	Initial sediment mass (kg) available in reach at beginning of day on simulation start date (t=0)
SAMBOR	0.00002	0.9	50000000	1000000000			5E+11
Reach 1	0.00002	0.9	50000000	1000000000			5E+11
Reach 2	0.00002	0.9	50000000	1000000000			5E+11

Figure A6.6. "Reach Specifications" data worksheet.

a) **Flow Routing Flow routing coefficient δ.** This data column is required only if the Storage-Outflow routing method is selected in the "Simulation Specifications" worksheet within the input file. The specified coefficient value will be used in the pair of reach routing Eq. (A2.1) and Eq. (A2.2) for the corresponding reach.

b) **Flow Routing Flow routing exponent γ.** This data column is required only if the Storage-Outflow routing method is selected in the "Simulation Specifications" worksheet within the input file. The specified exponent value will be used in the pair of reach routing Eq. (A2.1) and Eq. (A2.2) for the corresponding reach.

c) **Ponding storage volume (m^3).** This data column is required only if the Storage-Outflow routing method is selected in the "Simulation Specifications" worksheet within the input file. The specified value will be used in the pair of reach routing Eq. (A2.1) and Eq. (A2.2) for the corresponding reach.

d) **Initial reach storage (m^3) at beginning of day on user-specified simulation start date.** This information is required because the model predicts end-of-period storage volume values for every reach. To predict the end-of-period storage volume for the simulation start date, the user must supply the beginning of period storage volume for the simulation start date. This value is identical to the end-of-period storage in the date before the specified simulation start date.

e) **Sediment routing coefficient "a".** This information is required only if the user chooses the "Specify a separate coefficient and exponent for each reach" calibration option in the reach sediment discharge category (within the "Simulation Specifications" worksheet in the input file). The specified coefficient value will be used in the sediment routing Eq. (A2.3) for the corresponding reach.

f) **Sediment routing coefficient "b".** This information is required only if the user chooses the "Specify a separate coefficient and exponent for each reach" calibration option in the reach sediment discharge category (within the "Simulation Specifications" worksheet in the input workbook). The specified coefficient value will be used in the sediment routing Eq. (A2.3) for the corresponding reach.

g) **Initial sediment mass (kg) available in the reach at beginning of simulation start date.** This represents the amount of sediment (kg) available in storage (bed sediment) in each reach at the beginning of the day on the simulation start date. (Sediment in suspension at the beginning of simulation in all reaches is assumed to be zero. Absence of sediment in suspension in reaches during the first simulation time period will briefly affect the quantity of sediment that is scoured from (or that settles onto) the river channel bed. For this reason, you may wish to run the simulation for a few extra days, or simply ignore the first few days of results.). An accurate value may be difficult to determine in practice, in which case the user could assume some large value of initial sediment availability, simply to prevent complete exhaustion of sediment supply in reaches. Relative Changes in sediment mass stored in the reach from the initial value assumed would then become more important than absolute changes. This initial sediment mass value is required because the model predicts end-of-period sediment mass values for every reach. To predict the end-of-period sediment mass on the simulation start date, the user must supply the beginning of period mass for the simulation start date. This value is identical to the end-of-period mass in the date before the specified simulation start date.

7. E-V-A-S

The "E-V-A-S" worksheet contains the Elevation (meters above mean sea level: mamsl)-Volume (m^3)-Area (ha)-Sediment (cumulative fraction) data for each reservoir in the modeled system.

Starting with the first column on the left, the user must specify exactly four columns of information for each reservoir, in the exact order in which they appear below:

a) Column 1: **Elevation data**
b) Column 2: **Water volume data**

c) Column 3: **Water surface area data**
d) Column 4: **Cumulative fraction (in the range from 0-1) of settled sediment to be stored below each corresponding elevation in Column 1 in each time step of simulation.**

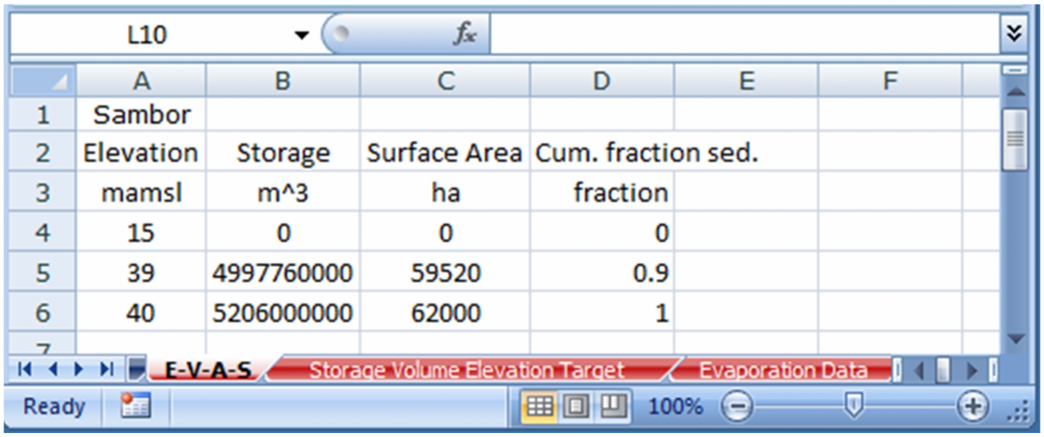
No blank columns should be placed between the sets of 4 columns (e.g., if your system includes 41 reservoirs, then you should populate 41 sets of 4 columns, or 41*4=164 columns of E-V-A-S data, with no blank columns). The first three rows are reserved for column headers and reservoir identification. Thus, data should be first entered on the fourth row. In the first row of the worksheet, above the first of the four column entered for each reservoir, users should enter the name of the reservoir to which the data correspond, exactly as the name appears in the "Network connectivity" worksheet.

The elevation, volume and area data are generally measured or estimated using GIS. These data are used for four purposes. First, the data is used in conjunction with each reservoir's empty and full supply level elevations to estimate each reservoir's active and dead storage capacity. Second, the data are used to determine the water surface elevation corresponding to the reservoir's storage in each time period, and therefore the capacities of discharge outlets and the head available for hydropower production. Third, the Area (ha) data are used to determine the reservoir's average surface area during each time period corresponding to each water level elevation, which is used to determine evaporation during each time period. Fourth, the sediment information is used to continually adjust the originally specified elevation-volume data (from the "E-V-A-S" worksheet) as the simulation proceeds to account for sediment accumulation in the water storage space. That is, less space is available to store water as sediment accumulates, and more space is available to store water as sediment is removed from the reservoir via sediment management techniques.

The cumulative fraction of sediment stored below different elevations in the reservoir depends on several factors, including the reservoir operating policy, reservoir shape, and predominant grain size of settling sediment. More information about how to specify a cumulative curve for a particular reservoir can be found in *Morris and Fan* [1998] and *Strand and Pemberton* [1987].

If the user does not specify any sediment storage information, the model will assume that sediment is continually deposited equally in the reservoir at all elevations. For example, if a reservoir's total water volume (dead and active) is stored over 20 m of depth, when sediment is deposited *SedSim* will reduce the available water storage capacity at each of the depths (i.e., reduce the cumulative water storage volume value for each elevation) in proportion to the fraction each depth represents out of the total 20 m differential.

When a sediment removal practice is simulated for a particular reservoir (e.g., flushing or general sediment removal), this sediment is assumed to be removed equally from all elevations in the reservoir. For flushing, this assumption is particularly appropriate because the flushing channel extends from the upstream end of the reservoir (at the highest elevation) to the base of the dam (the lowest elevation). Thus, when flushing occurs, some sediment is likely removed from every elevation in the reservoir's profile. When this sediment is removed, more volume at each elevation becomes available for water storage (i.e., there is a partial recovery of the elevation-volume curve towards its original profile).



	A	B	C	D	E	F
1	Sambor					
2	Elevation	Storage	Surface Area	Cum. fraction sed.		
3	mamsl	m^3	ha	fraction		
4	15	0	0	0		
5	39	4997760000	59520	0.9		
6	40	5206000000	62000	1		

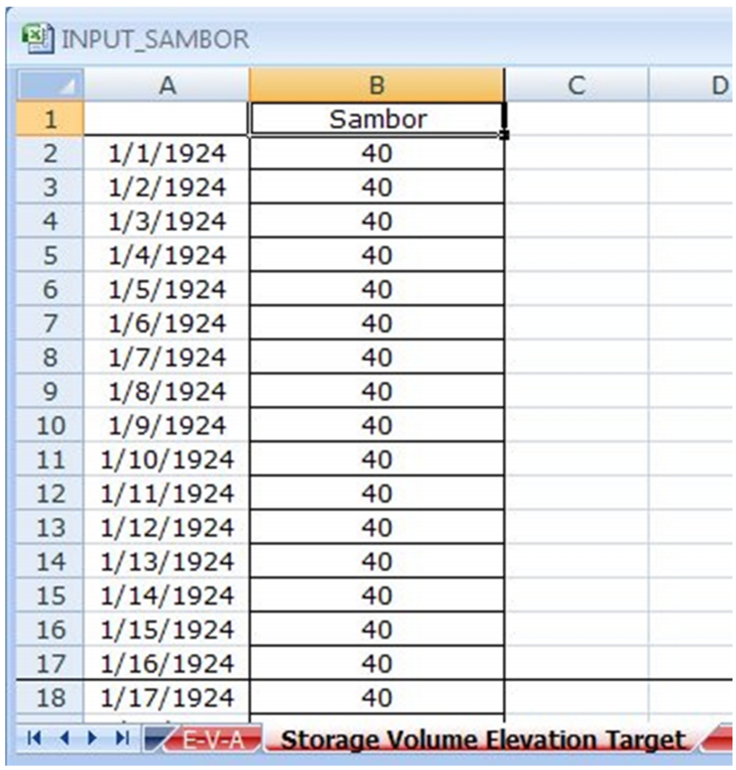
Figure A6.7. Portion of "E-V-A-S" worksheet of input data file.

8. Storage Volume Elevation Target

“Storage Volume Elevation Target” worksheet is only required if the elevation target option is selected for any reservoir in the reservoir operations goal column in the "Reservoir Specifications" worksheet in the input data file. Otherwise, this worksheet will not be used by the model, and thus can be ignored (deleted, left blank, or kept in its current state). The sheet is only required to contain time series of the end-of-day water elevation (mamsl) for reservoirs for which the elevation target option is selected in the reservoir operations goal column in the "Reservoir Specifications" worksheet in the input data file. The time series of targets must contain a target value for the end of the day the simulation starts, but not for the end of the day on the date before the simulation begins. Each column should represent a time series of elevation target values for a particular reservoir, whereas each row represents the elevation target values for all reservoirs for a particular date. As with all other time series sheets, time series data should begin on the second column and second row, dates should begin on the first column and second row, and the reservoir name should be placed on the first row of every time series column (beginning with the second column). The reservoir name in each column must be identical to the reservoir's name as defined in the "Network connectivity" worksheet in the input file. Data for more than just those reservoirs for which elevation targets will apply can be stored in the worksheet, as can data for more dates than just those contained within the simulation horizon. The model will locate and import only the data necessary to conduct the simulation.

9. Storage Volume Target

This worksheet is only required if the storage target option is selected for any reservoir in the reservoir operations goal column in the "Reservoir Specifications" worksheet in the input data file. Otherwise, this worksheet will not be used by the model, and thus can be ignored (deleted, left blank, or kept in its current state). The sheet is required to contain time series of the end-of-day water storage targets (m^3) for reservoirs for which the storage target options are selected in the reservoir operations goal column in the "Reservoir Specifications" worksheet in the input data file. The time series of targets must contain a value for the target for the end of the day the simulation starts, but not for the end of the day on the date before the simulation start date. Each column should represent a time series of storage target values for a particular reservoir, whereas each row represents the storage targets for all reservoirs for a particular date. As with all other time series sheets, time series data should begin on the second column and second row, dates should begin on the first column and second row, and the reservoir name should be placed on the first row of every time series column (beginning with the second column). The reservoir name in each column must be identical to the reservoir's name as defined in the "Network connectivity" worksheet in the input file. Data for more than just those reservoirs for which storage targets will apply can be stored in the worksheet, as can data for more dates than just those contained within the simulation horizon. The model will locate and import only the data necessary to conduct the simulation.


INPUT_SAMBOR

	A	B	C	D
1		Sambor		
2	1/1/1924	40		
3	1/2/1924	40		
4	1/3/1924	40		
5	1/4/1924	40		
6	1/5/1924	40		
7	1/6/1924	40		
8	1/7/1924	40		
9	1/8/1924	40		
10	1/9/1924	40		
11	1/10/1924	40		
12	1/11/1924	40		
13	1/12/1924	40		
14	1/13/1924	40		
15	1/14/1924	40		
16	1/15/1924	40		
17	1/16/1924	40		
18	1/17/1924	40		

E-V-A | Storage Volume Elevation Target

Figure A6.8. Portion of the “Storage Volume Elevation Target worksheet of the input file.

10. Evaporation Data

This worksheet is only required to be created if the user wants to account for evaporation during simulation of reservoir operations. “Evaporation Data” worksheet stores average monthly evaporation data (mm) for each reservoir. Each row corresponds to a different reservoir in the modeled system for which data exist. The reservoir name stored in each row must be identical to the reservoir's name as defined in the "Network connectivity" worksheet in the input file. Each column in this worksheet corresponds to a different month for which the average monthly evaporation (mm) is required. If no evaporation data is available for a particular reservoir, a row for the reservoir is not required. Do not rearrange the locations of columns, as the model searches each column in order (1 through the 12), assuming they are in chronological order.

Reservoir Name	January Evap. (mm)	February Evap. (mm)	March Evap. (mm)	April Evap. (mm)	May Evap. (mm)	June Evap. (mm)	July Evap. (mm)	August Evap. (mm)	September Evap. (mm)	October Evap. (mm)	November Evap. (mm)	December Evap. (mm)
Sambor	101	115	155	159	148	130	142	109	106	137	122	112

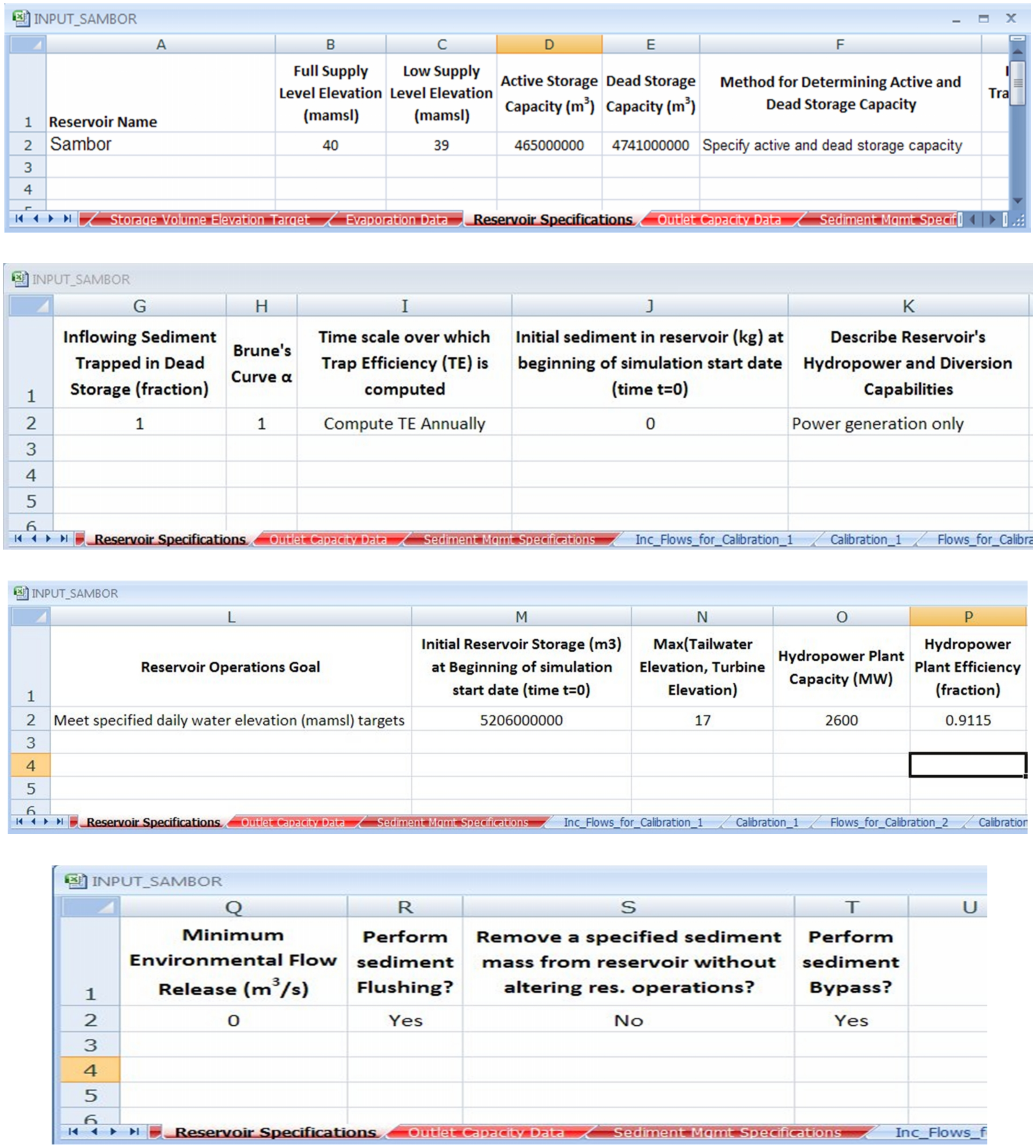
Figure A6.9. "Evaporation data" worksheet of input file.

11. Environmental Flow Data

This worksheet is only required to be created if the user wants to require minimum environmental flow releases (m^3/s) at any reservoirs during simulation. The "Environmental Flow Data" worksheet stores the minimum average daily flow (m^3/s) that must be released into the downstream channel at each reservoir site. This requirement is assumed to take precedence over rule curve-based requirements. For example, if the reservoir's pre-established operating policy dictates that no water should be released in a particular time period, the model will override this goal to make a release downstream to attempt to satisfy the minimum environmental flow requirement. Each row corresponds to a different reservoir in the modeled system for which data exist. The reservoir name stored in each row must be identical to the reservoir's name as defined in the "Network connectivity" worksheet in the input file. Each column in this worksheet corresponds to a different month for which the flow data are to be specified. If no data are available for a particular reservoir, a row for the reservoir is not required. Do not rearrange the locations of columns, as the model searches each column in order (1 through the 12), assuming they are in chronological order.

12. Reservoir Specifications

"Reservoir Specifications" worksheet stores a significant quantity of data (aside from time series) required to simulate sediment and water flows in reservoirs. Each row corresponds to a different reservoir in the modeled system for which data exist. The reservoir name stored in each row must be identical to the reservoir name as defined in the "Network connectivity" worksheet in the input file. Each column in this worksheet corresponds to a different category of information for which the user should supply data for all reservoirs for which the data category is relevant. (Each of these categories is introduced in detail below). If a particular data column does not apply to a particular reservoir, no input is required in that column. Do not rearrange the locations of columns from the order in which they appear below, as the model searches in set columns for specific information.


INPUT_SAMBOR

	A	B	C	D	E	F
1	Reservoir Name	Full Supply Level Elevation (mamsl)	Low Supply Level Elevation (mamsl)	Active Storage Capacity (m^3)	Dead Storage Capacity (m^3)	Method for Determining Active and Dead Storage Capacity
2	Sambor	40	39	465000000	4741000000	Specify active and dead storage capacity
3						
4						

Storage Volume Elevation Target / Evaporation Data / Reservoir Specifications / Outlet Capacity Data / Sediment Mgmt Specif

INPUT_SAMBOR

	G	H	I	J	K
1	Inflowing Sediment Trapped in Dead Storage (fraction)	Brune's Curve α	Time scale over which Trap Efficiency (TE) is computed	Initial sediment in reservoir (kg) at beginning of simulation start date (time t=0)	Describe Reservoir's Hydropower and Diversion Capabilities
2	1	1	Compute TE Annually	0	Power generation only
3					
4					
5					

Reservoir Specifications / Outlet Capacity Data / Sediment Mgmt Specifications / Inc_Flows_for_Calibration_1 / Calibration_1 / Flows_for_Calibra

INPUT_SAMBOR

	L	M	N	O	P
1	Reservoir Operations Goal	Initial Reservoir Storage (m3) at Beginning of simulation start date (time t=0)	Max(Tailwater Elevation, Turbine Elevation)	Hydropower Plant Capacity (MW)	Hydropower Plant Efficiency (fraction)
2	Meet specified daily water elevation (mamsl) targets	5206000000	17	2600	0.9115
3					
4					
5					

Reservoir Specifications / Outlet Capacity Data / Sediment Mgmt Specifications / Inc_Flows_for_Calibration_1 / Calibration_1 / Flows_for_Calibration_2 / Calibration

INPUT_SAMBOR

	Q	R	S	T	U
1	Minimum Environmental Flow Release (m^3/s)	Perform sediment Flushing?	Remove a specified sediment mass from reservoir without altering res. operations?	Perform sediment Bypass?	
2	0	Yes	No	Yes	
3					
4					
5					

Reservoir Specifications / Outlet Capacity Data / Sediment Mgmt Specifications / Inc_Flows_f

Figure A6.10. Portions of "Reservoir Specifications" worksheet of input data file.

a) **Full supply level elevation (mamsl).** This information represents the upper elevation (mamsl) threshold of the active storage zone, and is used by the model to estimate each reservoir's dead and active storage capacity. If you know the dead and active storage capacity, skip this column and enter the capacity data in the two appropriate capacity columns (discussed below). The only reason the model attempts to determine dead and active storage capacity is to report in the model output separate estimates of the loss in storage capacity within each zone that results from sediment deposition. This elevation information is only required when the "Compute active and dead storage capacity using elevation-volume-area data and dead/active elevations" option is selected in the column (within the "Reservoir Specifications" worksheet) that represents the method for determining active and dead storage capacity (see below for a description of this column). If the user selects this option, indicating the low and full supply level elevations will be used to determine active and dead storage capacity, the model will import the specified upper and lower elevations and use them to interpolate over the Elevation-Volume-Area data (within the "E-V-A-S" worksheet) to determine the dead and active storage capacities. Note that the active storage zone is defined here as the zone of the reservoir within which water elevations are fluctuated for purposes of hydropower production, whereas the dead storage is defined as all storage that remains at an elevation below active storage zone (i.e., below the low supply level elevation).

b) **Low supply level elevation (mamsl).** This information represents the lower elevation (mamsl) threshold of the active storage zone, and is used by the model to estimate each reservoir's dead and active storage capacity. If you know the dead and active storage capacity, skip this column and enter the capacity data in the two appropriate capacity columns (discussed below). The only reason the model attempts to determine dead and active storage capacity is to report in the model output separate estimates of the loss in storage capacity within each zone that results from sediment deposition. This elevation information is only required when the "Compute active and dead storage capacity using elevation-volume-area data and dead/active elevations" option is selected in the column (within the "Reservoir Specifications" worksheet) that represents the method for determining active and dead storage capacity (see below for a description of this column). If the user selects this option, indicating the low and full supply level elevations will be used to determine active and dead storage capacity, the model will import the specified upper and lower elevations and use them to interpolate over the Elevation-Volume-Area data (within the "E-V-A-S" worksheet) to determine the dead and active storage capacities. Note that the active storage zone is defined here as the zone of the reservoir within which water elevations are fluctuated for purposes of hydropower production, whereas the dead storage is defined as all storage that remains at an elevation below active storage zone (i.e., below the low supply level elevation).

c) **Brune Curve Type (L=Low trapping; M=Median trapping; H=High trapping; number (fraction) = constant trapping).** Sediment trapping in reservoirs is given by Brune's curve [*Brune*, 1953]. *Brune* [1953] originally specified three curves, each fitted to different portions of his available data set. Type one of the following options into the cell for the reservoir of interest (type only the value appearing in quotation marks).

i. "L". This represents the *Brune* [1953] original low trapping curve (for colloidal/dispersed and fine-grained particles).
ii. "M". This represents the *Brune* [1953] original median curve
iii. "H". This represents the *Brune* [1953] upper (or high) trapping curve (for highly flocculated and coarse sediments)

iv. Enter a numeric fraction from 0-1 to specify a constant trapping efficiency instead of using the Brune curve (e.g. enter “0.4” for a constant trapping efficiency of 40% throughout simulation at the reservoir).

Note: If the user specifies no value in this cell for a particular reservoir, the default is to assume zero trapping efficiency (0%).

d) **Time scale over which Trap Efficiency (TE) is computed (A=Annual; M=Monthly).** This value is only required if the user specifies “L”, “M”, or “H” in the Brune Curve Type Column of the “Reservoir Specifications” worksheet (i.e., if the user elects to use Brune curve trapping instead of specifying a constant trapping efficiency). Type one of the following options into the cell for the reservoir of interest (type only the value appearing in quotation marks).

i. “A”. *A* represents *Annual*. This indicates the model should apply the *Brune* [1953] curve using Annual residence time (computed using data from the previous 365 days).
ii. “M”. *M* represents *Monthly*. This indicates the model should apply the *Brune* [1953] curve using Monthly residence time (computed using data from the previous 30 days).

To provide more detail on these two options, trapping in reservoirs in *SedSim* is determined using Brune's curve. Trap Efficiency depends on a reservoir's residence time. The first option computes the residence time based on the average reservoir storage (m^3) and average outflow volume (m^3) over the previous 30 days. The second option computes the residence time based on the average reservoir storage (m^3) and average outflow volume (m^3) over the previous 365 days.

Note: If the user specifies “L”, “M”, or “H” in the Brune Curve Type Column of the “Reservoir Specifications” worksheet but does not specify a value in the column described here, the default will be “A”, as described above. If the user elects to apply a constant trap efficiency in the in the Brune Curve Type Column of the “Reservoir Specifications” worksheet, no information from this worksheet will be used.

e) **Initial sediment in reservoir (kg) at beginning of simulation start date (time t=0).** This represents the amount of sediment (kg) available in storage (at the bottom of the reservoir rather than in suspension) in each reservoir at the beginning of the day on the simulation start date. (Sediment in suspension at the beginning of simulation in all reservoirs is assumed to be zero. Absence of sediment in suspension in reservoirs during the first simulation time period will briefly affect the quantity of sediment that settles in the reservoir, and that is discharged from the reservoir, in the first few days of simulation. For this reason, you may wish to run the simulation for a few extra days, or simply ignore the first few days of results.) This column represents sediment that is available to be released from the reservoir, and that exists in the active and/or dead storage zones. This option is designed to allow a simulation of a reservoir that has already experienced sedimentation. Hence, for a new reservoir, the value in this initial sediment availability column should be 0, as no sediment has accumulated in either zone by the start of simulation. Clearly, a new reservoir will have some sediment availability where the original river bed existed, but this model assumes none of this sediment is available to be released from the reservoir, and is therefore ignored. As with other initial (time zero) values, this is required because the model attempts to predict the end-of-period sediment mass on the simulation start date, so the user must supply the beginning of period mass for the simulation start date. This value is identical to the end-of-period mass in the date before the specified simulation start date.

f) **Describe Reservoir's Hydropower and Diversion Capabilities.** Select one of the following options from the drop-down menu:

i.) Power generation only
ii.) Diversion only
iii.) Power generation & diversion

If no drop-down menu is available, type one of the listed options into the cell exactly as it appears above. Leave the cell blank if the reservoir has neither power production nor diversion capabilities. As detailed in Chapter 2, the model simulates four different types of reservoirs. A reservoir can have (or not have) hydropower production capabilities, and can have (or not have) the capability to divert water away from the downstream channel and instead to another site within the modeled system. In this column, the user specifies which of the reservoir types described in Chapter 2 is applicable to the reservoir of interest. This column is designed for users to specify only whether the reservoir of interest has a hydropower and/or diversion capability.

g) **Reservoir operations goal.** Select one of the following options from the drop-down menu:

i.) Meet specified daily water elevation (mamsl) targets.
ii.) Meet specified daily water storage targets (m^3).

If no drop-down menu is available, type one of the listed options into the cell exactly as it appears above. This column allows the user to specify the operational goal of each reservoir. If sediment accumulation in the reservoir is negligible in comparison to the storage capacity, then this option will result in essentially the same policy one would establish using storage targets, because an elevation corresponding to every water storage value can be determined from the user-supplied Elevation-Volume data. However, if sediment accumulation in the reservoir is significant, the water elevation targets option allows specified elevations to be maintained in the reservoir over time, which may require that less water be maintained in storage as the simulation proceeds due to sediment accumulation in the reservoir's storage space.

h) **Initial reservoir storage volume (m^3) at beginning of simulation start date (time t=0).** This information is required because the model predicts end-of-period storage volume values for every reservoir. To predict the end-of-period storage volume for the simulation start date, the user must supply the beginning of period storage volume for the simulation start date. This value is identical to the end-of-period storage volume on the date before the specified simulation start date.

If the user specifies no value, the model default assumption is that the reservoir's initial water storage value is equal to the dead storage capacity (i.e., the water surface elevation is at the bottom of the active storage elevation and top of the dead storage elevation).

i) **Maximum of turbines' centerline elevation and reservoir's tailwater elevation (mamsl).** In this column, specify the maximum of the constant tailwater elevation (the elevation of the water in the channel immediately downstream of the reservoir) and the turbines' centerline elevation. The larger of these two values will serve as the lower elevation used to compute hydropower head (and therefore hydropower production) during each time period, as given in Chapter 2. The value specified in this cell is assumed to remain constant throughout simulation. The hydropower head during the time period is assumed to be the average difference between the reservoir's water elevation and the constant tailwater elevation at the beginning and end of each time period. These data are only required if the user has selected that the reservoir has hydropower capabilities.

j) **Hydropower plant capacity (MW).** In this column, specify the hydropower plant capacity (MW) for each reservoir. This value should represent the sum of the rated (nameplate) capacities of all installed generators. No combination of turbine flow, net head, and efficiency will be permitted to produce an amount of hydropower exceeding this plant capacity value. This information is only required if the user has selected that the reservoir has hydropower capabilities.

k) **Hydropower plant efficiency (fraction).** In this column, specify the hydropower plant efficiency. This value is assumed to remain constant throughout simulation (not assumed to be a function of head and discharge). This information is only required if the user has selected that the reservoir has hydropower capabilities. The value in this column will be used to compute hydropower production during each time period.

l) **Reservoir Length (m).** This is the reservoir length at the normal reservoir operating level. This input is used to simulate sluicing and density current venting. For sluicing, it is used to compute the Sedimentation Index (SI), which is used in *SedSim* to implement the *Churchill* [1948] method to compute reservoir trap efficiency during sluicing. For density current venting, this input is optional, as it is used to determine a default minimum venting efficiency value for the user if the user does not specify one.

m) **Perform sediment Flushing?** Select one of the following options from the drop-down menu:

i.) Yes
ii.) No

If no drop-down menu is available, type one of the listed options into the cell exactly as it appears above. In this column, specify whether or not sediment flushing should be attempted in the reservoir of interest. (Note that more detailed background information about flushing, and the approach to flushing taken by this model, is contained in Chapter 2). If you select "Yes", you must supply additional flushing information in (1) the "Flushing" worksheet, and (2) the "Outlet Capacity Data" worksheet. See descriptions of these two worksheets for more details. Also, sediment flushing can only be performed if the user chooses to perform the hydrologic simulation using the *SedSim* model.

n) **Remove a specified sediment mass from reservoir without altering reservoir operations?** Select one of the following options from the drop-down menu:

i.) Yes
ii.) No

In this column, specify whether or not general sediment mass removal should be simulated at this reservoir, via a technique that does not require reservoir operational changes (e.g., dredging). If no drop-down menu is available, enter either "Yes" or "No" into the cell for each reservoir. Any entry other than "Yes" (e.g., a blank cell) will result in no mass removal. (Note that more detailed background information about this technique, which results in net sediment removal from a reservoir without altering the reservoir's operations, is provided in Chapter 2). If you select "Yes", you must supply additional information in the "General Sediment Removal" worksheet.

o) **Perform Sediment Bypass?** Select one of the following options from the drop-down menu:

i.) Yes
ii.) No

In this column, specify whether or not sediment bypassing should be simulated at this reservoir. If no drop-down menu is available, enter either "Yes" or "No" into the cell for each reservoir. Any entry other than "Yes" (e.g., a blank cell) will result in no sediment bypassing. (Note that more detailed background information about sediment bypassing is provided in Chapter 2). If you select "Yes", you must supply additional information in the "Bypassing" worksheet.

p) **Perform Density Current Venting?** Select one of the following options from the drop-down menu:

i.) Yes
ii.) No

In this column, specify whether or not density current venting should be simulated at this reservoir. If no drop-down menu is available, enter either "Yes" or "No" into the cell for each reservoir. Any entry other than "Yes" (e.g., a blank cell) will result in no density current venting. (Note that more detailed background information about density current venting is provided in Chapter 2). If you select "Yes", you must supply additional information in (1) the "Density Current Venting" worksheet, and (2) the "Outlet Capacity Data" worksheet.

q) **Perform Sluicing?** Select one of the following options from the drop-down menu:

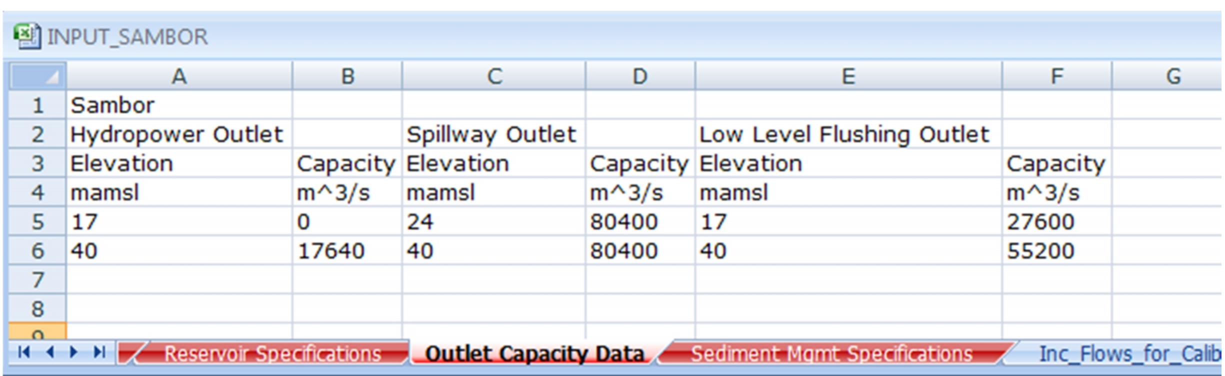
i.) Yes

ii.) No

In this column, specify whether or not sluicing should be simulated at this reservoir. If no drop-down menu is available, enter either “Yes” or “No” into the cell for each reservoir. Any entry other than “Yes” (e.g., a blank cell) will result in no sluicing. (Note that more detailed background information about density current venting is provided in Chapter 2). If you select "Yes", you must supply additional information in (1) the "Sluicing" worksheet, and (2) the "Outlet Capacity Data" worksheet.

13. Outlet Capacity Data

“Outlet Capacity Data**”** worksheet provides elevation vs. discharge capacity tables for every outlet that will be operated on each reservoir. This worksheet is only required if the user chooses to perform a hydrologic simulation using the *SedSim* Model. For every outlet at every reservoir, the user must supply two columns of data (elevation and discharge, from left to right). The number of outlets for which data must be provided for a particular reservoir will depend on the number of outlets the reservoir has, which is strictly dictated by the reservoir type (as selected in the "Reservoir Specifications" worksheet). More detailed discussion of outlets is provided in Chapter 2. Specifically, Figure A2.4 describes the number and types of outlets required for each reservoir type. For example, if a model is being built for ten reservoirs, and every reservoir has the same basic capability (hydropower production), then only two outlet types are required per reservoir (Hydropower Outlet and Overflow Outlet). For these ten reservoirs, a total of 10*2 = 20 pairs (40 columns) of elevation vs. max. discharge data must be supplied by the user. If flushing were to be performed in each of the ten reservoirs, an additional 10 outlets would be required for a total of 80 columns. The most outlets required for a reservoir occurs in the case of a diversion dam. For example, if the ten reservoirs were instead hydropower/diversion reservoirs with flushing capabilities, a total of 10*4 = 40 outlets would be required.


INPUT_SAMBOR

	A	B	C	D	E	F	G
1	Sambor						
2	Hydropower Outlet		Spillway Outlet		Low Level Flushing Outlet		
3	Elevation	Capacity	Elevation	Capacity	Elevation	Capacity	
4	mamsl	m^3/s	mamsl	m^3/s	mamsl	m^3/s	
5	17	0	24	80400	17	27600	
6	40	17640	40	80400	40	55200	
7							
8							

Reservoir Specifications | Outlet Capacity Data | Sediment Mgmt Specifications | Inc_Flows_for_Calib

Figure A6.11. “Outlet Capacity Data” worksheet

Every time outlets for a particular reservoir are defined, the name of the reservoir for which the outlet capacity vs. elevation data are provided must be listed in the first row of the first of all the elevation-discharge columns defined for a particular reservoir. (The reservoir name at the top of each column must be identical to the reservoir's name as defined in the "Network connectivity" worksheet in the input file). For example, if a particular reservoir has four outlets, then a total of 8 consecutive columns should be defined for the reservoir, with the name of the reservoir appearing only once at the very top of the first of the 8 columns.

Every time a new outlet for a reservoir is defined, the user should select the outlet type from a drop-down menu in the second row in the column in which the elevation data are provided (the left-hand column in each pair of two elevation-discharge columns). If no drop-down menu is available, type one of the listed options into the cell exactly as it appears below. For example, if a particular reservoir has four outlets, then an outlet type should be selected four times, each in the second row of the elevation data column. The drop-down menu offers the following six options:

i. Controlled Outlet
ii. Hydropower Outlet
iii. Diversion Outlet
iv. Hydropower/Diversion Outlet
v. Spillway Outlet
vi. Low level outlet

Data in each column should not begin until the fifth row. This is only to allow space for the user to list data type headings (e.g., "Flow") and data units ("cms"), if desired (this is not a requirement).

Data for more than just those reservoirs that will be modeled in the current simulation can be stored in the worksheet. The model will use only the data for those reservoirs that will be modeled. This saves time in the input file preparation process in instances in which one wishes to run simulations that explore different of reservoir development.

General Comments regarding Sediment Management Specifications Worksheets

The input file can contain up to five different sediment management worksheets:

a) Flushing
b) Sluicing
c) Density Current Venting
d) General Sediment Removal
e) Bypassing

The "Flushing", "Sluicing", and "General Sediment Removal" worksheets have similar formatting requirements. Likewise, the "Density Current Venting" and "Bypassing" worksheets have similar formatting requirements. Thus, common formatting requirements are presented here before each of the worksheets is presented, to avoid repeating this information in the sections for each individual worksheet.

Note that multiple sediment management techniques can be simulated in the same reservoir at different times. However, flushing, sluicing and density current venting cannot be simulated concurrently. Any management technique being simulated will be allowed to finish before a new technique is begun. For example, If sluicing is being simulated at a particular reservoir and flushing is meanwhile scheduled to occur, the start of flushing will be delayed until sluicing is completed.

Comments on “Flushing”, “Sluicing”, and “General Sediment Removal” worksheets

Each worksheet is only required if the user will implement the corresponding sediment management technique in any reservoir (e.g., if you specify "Yes" in the Flushing column of the “Reservoir Specifications” worksheet, then you need a “Flushing” worksheet to store additional information). For every in which a sediment management technique is to be applied to a reservoir, a new block of 12 (for “Flushing”), 8 (for “Sluicing”), and 5 (for “General Sediment Removal”) columns of information must be supplied by the user. For example, if a model is being built for ten reservoirs, and both Flushing and General Sediment Removal are to be conducted at some time during simulation at every one of the ten reservoirs, then a total of 10*12 + 10*5 = 170 columns of information must be supplied by the user.

Within each worksheet, the name of the reservoir for which the technique and data apply must be listed in the first row and in the first of the set of columns (e.g., in the “Sluicing” worksheet, the reservoir name should appear in (row 1, column 1) for the data set of the first reservoir in which sluicing will occur, in (row 1, column 9) for the data set for the second reservoir in which sluicing will occur, etc. The reservoir name should only be listed once in each worksheet for each reservoir in which the corresponding sediment management technique will be simulated.

The reservoir name at the top of each column must be identical to the reservoir's name as defined in the "Network connectivity" worksheet in the input file. Data for more than just those reservoirs for which you have selected to implement a sediment management technique can be stored in the worksheet, as the actual implementation of the technique is controlled by the preferences selected in the "Reservoir Specifications" worksheet. The model will use only the data for those reservoirs at which sediment management techniques will actually be implemented.

Each row in these three worksheets, starting with the third row, represents a different event date. The events should appear in chronological order. For example, if Sluicing will be simulated twice at one reservoir during the simulation horizon, from 9/1/1980 to 9/15/1980, as well as from 8/3/1985-8/8/1985, data corresponding to each of these separate events should appear in separate, consecutive rows . If some of the required user input data will remain the same every time the technique is simulated (e.g., the flushing duration, flushing minimum discharge, etc.), then the user is only required to enter this information in the first row (corresponding to the first event). *SedSim* will import information from the first row when the user does not specify information for future events. If particular specifications are different for different events (e.g., the target sluicing water surface elevation), then the user can also just specify new information in each row. For example, if ten sluicing events are scheduled in ten different rows in column 1, then the user can specify ten different sets of input data in the input data columns.

Comments on “Density Current Venting” and “Bypassing” worksheets

In these two worksheets, each row corresponds to a different reservoir in the modeled system for which data exist. The reservoir name stored in the first column of each row must be identical to the reservoir name as defined in the "Network connectivity" worksheet in the input file. Each column in this worksheet corresponds to a different category of information for which the user should supply data for all reservoirs for which the data category is relevant. (Each of these categories is introduced in detail below). If a particular data column does not apply to a particular reservoir, no input is required in that column. The Data entry should begin on the second row and second column. Do not rearrange the order of columns from how they appear in each section below, as the model searches in set columns for specific information.

14. Flushing

The following information must be supplied by the user for every reservoir at which flushing will be simulated. Some user inputs are described below as *Optional*, meaning these inputs are extra features that are not required to run a simulation. The columns should be specified in exactly the order (left to right) in which they are listed below.

INPUT_SAMBOR

	A	B	C	D	E	F	G
1	Sambor						
2	Flushing						
3	Date: Beginning of Drawdown	Flushing Duration (days)	Max. Flushing water surface elevation (mamsl)	Min. Flushing Discharge (m3/s)	Long Term Capacity Ratio (LTCR)	Fraction of Flushed Sediment Removed from Active Storage Zone	Minimum reservoir inflow for drawdown (above which drawdown still occurs) (m^3/s)
4	5/1/1924	3	20	13,800	0.15	0.67	13,800
5	5/1/1925	3	20	13,800	0.15	0.67	13,800
6	5/1/1926	3	20	13,800	0.15	0.67	13,800
7	5/1/1927	3	20	13,800	0.15	0.67	13,800
8	5/1/1928	3	20	13,800	0.15	0.67	13,800
9	5/1/1929	3	20	13,800	0.15	0.67	13,800
10	5/1/1930	3	20	13,800	0.15	0.67	13,800
11	5/1/1931	3	20	13,800	0.15	0.67	13,800
12	5/1/1932	3	20	13,800	0.15	0.67	13,800
13	5/1/1933	3	20	13,800	0.15	0.67	13,800

Evaporation Data | Reservoir Specifications | Outlet Capacity Data | Sediment Mgmt Specifications | Inc_Flows_for_Calibration_1 | Ca

Figure A6.12. “Flushing” worksheet of input file.

a) **Target Date: Beginning of Drawdown.** In this column, enter the calendar date(s) defining when reservoir drawdown for flushing can begin (if the inflow rate criterion defined below is satisfied) and the number of days of flushing. Every time flushing (and therefore drawdown) are to occur, a new date should be listed in a new row in the column for this reservoir.

b) **Flushing Duration.** This is the number of days during which flushing criteria (flow and elevation requirements discussed below) must be satisfied, and does not include any days that only serve to draw down (empty) the reservoir.

c) **The maximum flushing water surface elevation (WSE).** This is the maximum elevation of water in the reservoir that will still result in successful flushing. (For example, if the original river bed elevation, and/or low-level outlet invert elevation, is 56 masl, then 56 masl will be the target drawdown elevation. However, flushing can still be successful if the reservoir is not able to fully draw down to 56 masl. If, for example, successful flushing will still occur if the reservoir is drawn down to 58 masl (2 m above the target) because free flow conditions are relatively well maintained, then the user would input 58 masl into this column for the flushing date(s) of interest.

d) **Minimum inflow rate at which drawdown is initiated.** *Optional*. The minimum inflow rate that will permit the drawdown process to be initiated on or after the target date specified in the date column. The user must specify the date on which drawdown should first be considered. The model waits until this specified date to consider drawdown, but does not actually initiate drawdown until the reservoir inflow exceeds the value specified in this cell. This will prevent a drawdown that begins too early in the dry season, before flows at the beginning of the wet season begin to increase. If the user does not enter a value in this column, the model will assume that no such threshold exists for the initiation of drawdown.

e) **Flushing channel bottom width (m)**. This is the width of the bottom of the channel that will form during flushing. Assuming the channel will form a trapezoidal cross-section over time, this width represents the (smaller) bottom width of the trapezoid. This value is used to determine the dimensions of the flushing channel, which is used to determine the quantity of sediment removed during flushing as the flushing channel grows over time. The channel width can be approximated fairly well as a function of flushing discharge, though it also likely depends on channel slope and sediment properties. In absence of field measurements or other data, *Atkinson* [1996] suggests estimating this property using the equation given below.

   If the user does not specify any channel width, the model will use this relationship below to determine channel width as a function of the user-specified minimum flushing flow value (the reservoir inflow (m3/s) below which flushing is assumed not to be successful on a flushing day).

   $W_f = 12.8 Q_f^{0.5}$

   where W_f is the width (m) of the channel formed during flushing and Q_f is the flushing discharge (m^3/s).

   This value cannot be different for each flushing date, so the value is imported from the first row of flushing data.

f) **Flushing channel average side slope (m/m, 1 horizontal to SS_f vertical).** This is the slope of the side walls of the incised channel formed during flushing. This value is used to determine the dimensions of the flushing channel, which is used to determine the quantity of sediment removed during flushing as the flushing channel grows over time. Flushing channel side slopes can vary widely, and depend upon the degree of sediment consolidation, sediment properties, the depth of the deposits through which the incised channel is cut, and the extent of water level fluctuation during flushing. In the absence of field measurements or other data, *Atkinson* [1996] suggests using the formulation proposed by *Migniot* [1981], as given below. If the user does not specify any side slope, the model will use this relationship to determine side slope as a function of the user-specified sediment density.

$$\text{Side slope } = \frac{31.5}{5} \rho_d^{4.7} \left(\frac{1}{10}\right)$$

where ρ_d is the average dry density (t/m^3) of the sediment through which the flushing channel will be cut.

This value cannot be different for each flushing date, so the value is imported from the first row of flushing data.

g) **Maximum flushing drawdown rate (m/day)**. *Optional*. This is the maximum rate at which the water level of the reservoir can be drawn down per day during the drawdown phase of sediment flushing. Rapid drawdown of a reservoir can lead to bank failure, landslides, or similar events, in which large quantities of soil fall into the reservoir storage space. In the absence of better information, the user may wish to restrict the drawdown rate to within the range of 1-3 m/day.

h) **Minimum flushing discharge**. In this column, enter the minimum discharge through the low level outlets that will still result in successful flushing. No removal of sediment from the reservoir's settled sediment storage will occur if this minimum flow rate criterion is not satisfied, which will extend the number of total days the reservoir spends trying to meet the flushing duration goal.

i) **Reservoir bottom width (m).** This is the representative bottom width of the reservoir. This value is used in *SedSim* to determine the relative volume of the reservoir, which, when compared to the volume of the channel formed during flushing, aids in determining the quantity of sediment released during a flushing event. It is suggested to use the widest section of the reservoir bottom close to the base of the dam, as a wider value will produce a more conservative flushing result (a wider reservoir results in lower quantities of sediment removed during flushing events).

This value cannot be different for each flushing date, so the value is imported from the first row of flushing data.

j) **Reservoir average side slope (m/m, 1 horizontal to SS_{res} vertical).** This is the representative bank side slope of the reservoir. This value is used in *SedSim* to determine the relative volume of the reservoir, which, when compared to the volume of the channel formed during flushing, aids in determining the quantity of sediment released during a flushing event.

This value cannot be different for each flushing date, so the value is imported from the first row of flushing data.

k) **Coefficient value, k, for sediment load generation during Flushing (kQ^m).** *Optional*. Instead of computing the sediment loads discharged during flushing via the methods described in the Flushing section of Chapter 2, the user can instead specify parameters to be used in the equation kQ^m to determine sediment discharge from the reservoir each day during flushing as a function of reservoir outflow). Sediment discharge during a flushing day (kg) is determined by $kQ^m*Q(dt)$, where Q (m^3/s) is the reservoir inflow and dt is the daily time step in seconds. Entering information in this column will dictate the use of this method for sediment flushing discharge, whereas leaving this column blank will dictate the use of the long term capacity ratio for the flushing simulation.

l) **Exponent value, m, for sediment load generation during Flushing (kQ^m).** *Optional*. Instead of computing the sediment loads discharged during flushing via the methods described in the Flushing section of Chapter 2, the user can instead specify parameters to be used in the equation kQ^m to determine sediment discharge from the reservoir each day during flushing as a function of reservoir outflow). Sediment discharge during a flushing day (kg) is determined by $kQ^mQ*(dt)$, where Q (m^3/s) is the reservoir inflow and dt is the daily time step in seconds. Entering information in this column will dictate the use of this method for sediment flushing discharge, whereas leaving this column blank will dictate the use of the long term capacity ratio for the flushing simulation.

15. Sluicing

The following information must be supplied by the user for every reservoir at which sluicing will be simulated. Some user inputs are described below as *Optional*, meaning these inputs are extra features that are not required to run a simulation. The columns should be specified in exactly the order (left to right) in which they are listed below.

Some comments on default sluicing assumptions. Before describing the user inputs specifically, some comments are important regarding default assumptions. Except for the sluicing start and stop dates each year, the user is only required to specify assumptions for the categories above in the row corresponding to the first sluicing event. As long as preferences (e.g., target drawdown elevation) are established for the first sluicing event, the model will continue to use these values if the user neglects to specify preferences for future sluicing dates. For categories including the sluicing inflow-based starting criteria, drawdown rate, and refill rate, the model assumes the constraints do not exist if values of zero are specified for the first sluicing event (or if cells are left blank). For the sluicing drawdown elevation, if no value is specified the default is Elevation 0 masl. For power production during sluicing, if no value is stored in the first row, then the model assumes a default that no power is produced during sluicing.

a. **Beginning date of sluicing.** This is the first date on which drawdown for sluicing will begin. Application of the Churchill curve to determine sediment trapping begins on this date. If sluicing is to occur annually, the user must specify this date for every year in which sluicing will occur. Sluicing is typically performed for an extended period of time when water and sediment inflows are high (e.g., the monsoon season). To prevent the majority of inflowing sediment from depositing in the reservoir, sluicing should be performed for as long as possible during the season in which sediment production is highest.

b. **Sluicing starting criterion: minimum reservoir inflow rate (m^3/s).** *Optional.* This input is optional. If the reservoir inflow is lower than this value on the sluicing beginning date, the start of sluicing will be delayed by one day, and the condition will be checked again on the next day. The purpose of this option is to allow the user to avoid initiation of drawdown for sluicing during conditions that are not typical of high sediment inflows. For example, if the monsoon season begins in October on average, the user might specify 10/1 as the sluicing date every year. However, in a given year the monsoon might actually begin in November. This optional input is thus an extra check that could hold sluicing off until the high inflows actually begin in a given year. If sluicing is delayed, the original sluicing duration will be maintained (as defined by the number of days between the user-specified beginning and ending dates).

c. **Ending date of sluicing.** This is the last date on which sluicing will still occur. After this date, the reservoir operating policy will resume with the pre-existing operating policy.

d. **Sluicing stopping criterion: minimum reservoir inflow (m^3/s).** *Optional.* This input is optional. If the reservoir inflow is higher than this value on the sluicing ending date, the end of sluicing will be delayed by one day, and the condition will be checked again on the next day. The purpose of this option is to allow the user to avoid ending sluicing if reservoir inflows are high for longer than expected, in which case extending the duration of sluicing could be beneficial from a sediment management perspective.

e. **Target sluicing drawdown water surface elevation (mamsl) or storage (m^3).** This is the reservoir water surface elevation or storage to which the reservoir will be drawn down to begin the sluicing process. The extent to which the reservoir is drawn down affects the energy slope and ultimately the percentage of sediment that will pass through the reservoir during sluicing. In the absence of better information, the target elevation could be set to an elevation at or slightly above the mid-level gates.

f. **Maximum sluicing drawdown rate (m/d).** *Optional*. This is the maximum rate at which the water level of the reservoir can be drawn down per day during the drawdown phase of sediment sluicing. Rapid drawdown (and/or refill) of a reservoir can lead to bank failure, landslides, or similar events, in which large quantities of soil fall into the reservoir storage space. In the absence of better information, the user may wish to restrict the drawdown rate to within the range of 1-3 m/day.

g. **Maximum sluicing refill rate (m/d).** *Optional*. This is the maximum rate at which the water level of the reservoir can be refilled per day upon the completion of sluicing. In the absence of better information, the user may wish to restrict the refill rate to 4 m/day or less.

h. **Does hydropower production occur during sluicing**? Valid responses are either "Yes" or "No". If sluiced sediment is of high concentration for a long duration, and/or contains significant quartz content, hydropower-related infrastructure (e.g., turbines) can be damaged due to abrasion if power is produced during sluicing operations.

16. Density Current Venting

The following information must be supplied by the user for every reservoir at which density current (or turbidity current) venting will be simulated. Some user inputs are described below as *Optional*, meaning these inputs are extra features that are not required to run a simulation. The columns should be specified in exactly the order (left to right) in which they are listed below.

a. **Minimum venting efficiency (%).** This represents the lowest acceptable percentage of sediment removal that must occur for density current venting to be an attractive option (e.g., 35%). In determining this value, the user should weigh the relative importance of releasing sediment compared to the water that will be wasted during venting without power production.

   If the user does not specify a minimum venting efficiency, Figure 14.13 from *Morris and Fan* [1998] is used to establish a default value based on the reservoir length (km), using the following equation:

   Min. Efficiency = 0.5384 - 0.08*ln(Reservoir Length)

b. **Minimum reservoir water surface elevation (mamsl) during density current venting.** *Optional***.** Density current venting will not be allowed to reduce the water surface elevation below this specified elevation. The user should leave this cell blank if no minimum level exists, in which case venting will proceed until completed. Note that if the reservoir's water surface elevation approaches this minimum elevation, there exists the possibility that flow releases through the low level outlets for venting may be significantly reduced ($< Q_{in}(t)$) or even entirely eliminated, because any releases in this circumstance are first allocated to satisfying minimum hydropower production requirements.

c. **Maximum concentration (mg/l) of sediment released from reservoir during density current venting**. *Optional*. This input is optional. If the sediment mass released during density current venting divided by water volume released from the hydropower and low level outlets during venting cannot achieve this target 'concentration' (total mass/total volume), extra water will be released from the hydropower outlets (up to their capacity), and if this still does not achieve the target concentration, more water will be released from the mid-level outlets to attempt to achieve the target level. *SedSim* will not reduce the release of the density current flow from the low-level outlets in order to satisfy this target concentration, as such a practice could theoretically reduce the effectiveness of the density current release.

d. **Continue venting if max concentration exceeded?** If the user specifies a maximum concentration (mg/l) of sediment released from the reservoir during density current venting, the reservoir will attempt to meet this target by releasing additional clear water through available outlets, if necessary. The option described here allows the user two options: (1) to continue density current venting despite the inability of the reservoir to satisfactorily dilute the sediment released during the venting process (enable this option by entering “Yes”), and (2) to end density current venting due to the inability of the reservoir to satisfactorily dilute the sediment released during the venting process (enable this option by entering “No”).

e. **Reservoir bottom width (m).** This input is used in Eq. (A2.11) as part of the *SedSim* procedure to determine venting efficiency during density current venting events.

f. **Reservoir bed slope (m/m).** This input is used in Eq. (A2.11) as part of the *SedSim* procedure to determine venting efficiency during density current venting events.

g. **Minimum daily power requirement during density current venting (MW).** *Optional*. During density current venting, water will be released through available hydropower outlets to satisfy this minimum power production requirement, subject to hydropower outlet capacity-elevation constraints. While the *SedSim* approach to density current venting is to attempt to release the reservoir’s inflow (minus evaporation) through the low level outlets, thus maintaining the water surface elevation, any additional releases to satisfy this minimum power requirement will result in a more significant reduction in the water surface elevation of the reservoir. If the user also specifies a minimum water surface elevation during density current venting and the reservoir reaches this minimum elevation, priority is first given to satisfying the minimum hydropower production requirements, after which remaining releases are allocated to the low level outlets for venting flow release.

17. General Sediment Removal

The following information must be supplied by the user for every reservoir at which the user wishes to remove a specified sediment mass during a specified period of time without explicitly simulating the process. Some user inputs are described below as *Optional*, meaning these inputs are extra features that are not required to run a simulation. The columns should be specified in exactly the order (left to right) in which they are listed below.

a) **Removal start date.** This is the calendar date on which to begin removing sediment mass.

b) **Removal duration (days).** Specify number of days over which the specified sediment mass should be removed during each event. The sediment mass to be removed will be equally distributed among this number of days.

c) **Sediment mass removal (tons).** Specify the sediment mass to be removed during each event. This mass will be equally distributed over the removal duration.

d) **Destination element name.** Specify the user-defined (in the "Network connectivity" worksheet) name of the element into which the removed sediment mass will be deposited. If the user leaves this cell blank, the model's default assumption is to discharge this sediment out of the modeled system (the modeled system permanently loses this mass).

e) **Fraction of sediment removed from active storage zone.** Specify the fraction of sediment that is removed from the active storage zone when the sediment is removed from the reservoir during each event. The remaining fraction of sediment is assumed to be removed from the dead storage zone. If no value is entered, the model maintains the following default percentages: 50% of removed sediment is removed from the active storage zone, while the remaining 50% is removed from the dead storage zone.

18. Bypassing

The following three columns of information must be supplied to perform a sediment bypass around a reservoir. The columns should be specified in exactly the order (left to right) in which they are listed below.

1. **Minimum Bypass flow rate (m^3/s).** Specify the minimum reservoir inflow rate at which the sediment bypass is opened and sediment and flow begins to be discharged around the reservoir. If the inflow rate is lower than this value, the sediment and water will enter the reservoir without being bypassed.

2. **Bypass discharge capacity (m^3/s).** Specify the flow capacity of the sediment bypass. If the reservoir inflow rate exceeds this value, any inflow in excess of the bypass discharge capacity will enter the reservoir. However, only a fraction of the sediment concentration in this flow will enter the reservoir, whereas the remaining fraction of sediment will be distributed into the bypass. This fraction must be specified by the user, as described below.

3. **Fraction of sediment load in reservoir inflow.** The model's default assumption is that sediment is partitioned between the bypass and reservoir in proportion to the fractions of total inflow that are distributed into the bypass and reservoir. The user should thus enter nothing in this column if this is the desired assumption. Alternatively, the user can specify what fraction of the sediment that would otherwise have entered the reservoir (based on the proportion of total inflow that enters the reservoir) should instead be distributed into the bypass. This option was implemented to reflect that concentration increases with depth of flow, and thus the bypass may remove more of the inflowing sediment than just the proportion of flow diverted into the bypass.

19. IncFlowsCalibration1

The *SedSim* model will automatically create this worksheet if it is needed. This worksheet is only required if (1) the user chooses to perform internal calibration of incremental sediment load coefficients (i.e., selects the "Calibrate a coefficient for each incremental inflow location" option in the preferences in the main .xlsm model file); or (2) the user chooses to use coefficients that were previously calibrated within this worksheet (i.e., selects the "Use coefficients calibrated in most recent simulation." option in the preferences in the main .xlsm model file). Once the worksheet is created, do not modify the contents of this worksheet. The worksheet contains time series of the daily average incremental flow rates (m^3/s) that enter every reach or reservoir location in the modeled system.

20. Calibration1

The *SedSim* model will automatically create this worksheet if it is needed. This worksheet is only required if (1) the user chooses to perform internal calibration of incremental sediment load coefficients (i.e., selects the "Calibrate a coefficient for each incremental inflow location" option in the preferences in the main .xlsm model file); or (2) the user chooses to use coefficients that were previously calibrated within this worksheet (i.e., selects the "Use coefficients calibrated in most recent simulation." option in the preferences in the main .xlsm model file). Once the worksheet is created, do not modify the contents of this worksheet. The worksheet contains time series of the daily average incremental sediment loads that enter every reach or reservoir location in the modeled system (in kg/day). The incremental flows, Q(t), in the "Inc Flows forCalibration 1" worksheet are used as input to the incremental load generation function, $cQ(t)^d*Q(t)*\Delta t$, to generate daily incremental sediment loads at the location represented by each column. This worksheet is used as a calibration worksheet, because the value of c in the sediment generation function is contained in a cell at the bottom of the time series that is manipulated by Excel's LP solver until the average annual sediment load matches the desired value. The desired value should be provided in the "Sediment Loads" worksheet.

21. FlowsCalibration2

The *SedSim* model will automatically create this worksheet if it is needed. This worksheet is only required if the user chooses either of the following two options in the preferences in the main “SedSim.xlsm” file: (1) Calibrate a coefficient for each reach; or (2) Use coefficients calibrated in most recent simulation. Once the worksheet is created, do not modify the contents of this worksheet. The worksheet contains the time series of the daily average flow rates out of each reach (m^3/s) in the unregulated system. Thus, these flows simply represent the sum of all incremental flows that enter points upstream of the location of interest.

22. Calibration2

The *SedSim* model will automatically create this worksheet if it is needed. This worksheet is only required if the user chooses either of the following two options in the preferences in the main “SedSim.xlsm” file: (1) Calibrate a coefficient for each reach; or (2) Use coefficients calibrated in most recent simulation. The worksheet contains time series of the daily average sediment loads that flow out of every reach or reservoir location in the modeled system (in kg/day). The outflows, Q(t), in the "FlowsCalibration2" worksheet are used as input to the sediment load generation function, $aQ(t)^b*Q(t)*\Delta t$, to generate daily sediment loads flowing out of each location represented by each column. This worksheet is used as a calibration worksheet, because the value of a in the sediment generation function is contained in a cell at the bottom of the time series that is manipulated by Excel's LP solver until the average annual sediment load matches the desired value. The desired value is determined internally in the model by summing the values of the incremental sediment loads that are generated at all points upstream of the outflow point of interest.

7 Output Model File(s) Description

Overview of Model Output Workbook

Output file(s) are automatically created during the simulation and saved (using the user-specified file location and name in the "SedSim.xlsm" file). As discussed in Chapter 5 (the "SedSim.xlsm" file preferences), users have the option of creating up to two output files, or none at all. Currently, the two output files users can create are (1) a time series output for a variety of variables for all locations in the system to which the variables are applicable, and (2) a statistical summary of the time series output for a variety of variable values at all locations where they apply.

In the time series output file, each worksheet within the workbook corresponds to a different variable. Each column of time series data corresponds to a different location, which is listed at the top of each time series column. The number of variables (and system elements) included in the two output files depends on whether the system being simulated is Regulated or Unregulated. Fewer variables and locations are applicable in an unregulated simulation, as no reservoirs are present. In the statistical output file, in general, each worksheet contains output that corresponds to a unique combination of model variables and set of statistics taken over a particular time period. One worksheet will contain the mean, standard deviation, median, maximum and minimum of the values of a variable for each month at all system locations, whereas another worksheet will contain the same statistical manipulations but on an annual time scale. The automatically loaded worksheet labels, column and row labels, and worksheet/variable descriptions (in the first row of every worksheet) should clarify the organization of data in both files.

Worksheets in both files are color coded such that if the variable primarily relates to water the tab color is blue, whereas if the variable primarily relates to sediment the tab color is brown.

The model does not automatically generate figures (charts, graphs, tables, etc.) to graphically summarize the data in Excel. However, the user can easily access Excel's plotting capabilities to prepare any desired plots.

Each of the output files will now be discussed separately. The time series output file section provides a separate discussion of every worksheet included in the file, whereas the statistical output file section provides a more general discussion of the worksheets included in the file.

Time Series Output File

The following is a description of the information conveyed by each variable for which there is a worksheet in the time series output file. Worksheet names appear below in bolded text, although the actual worksheet names do not include the variable units listed below. The first row of each output file worksheet contains a brief description of the information contained in the worksheet, and those descriptions are given below to provide very brief summaries of the information included in the time series output file. However, much more detailed descriptions of the model output contained in each worksheet are provided immediately afterward.

- “Water Storage” Worksheet Description: Represents the total volume of water (m^3) stored in a reservoir or reach at the end of each time period.
- “Water Surface Elevation” Worksheet Description: Represents the elevation (mamsl) associated with the water storage in each reservoir.
- “Active Storage Volume” Worksheet Description: Represents the volume of water (m^3) held within the active storage zone at the end of each time period.
- “Dead Storage Volume” Worksheet Description: Represents the volume of water (m^3) held within the dead storage zone at the end of each time period.
- “Storage Volume Target Deviation” Worksheet Description: Represents the difference (m^3), or error, between the storage target for the end of each time period and the simulated reservoir storage at the end of each time period.
- “Stor. Vol. Target Deviation (%)” Worksheet Description: Represents the % difference (m^3), or error, between the reservoir storage target for the end of each time period and the simulated reservoir storage at the end of each time period.
- “Elevation Target Deviation” Worksheet Description: Represents the difference (mamsl), or error, between the reservoir elevation (mamsl) target for the end of each time period and the simulated reservoir elevation at the end of each time period.
- “Elevation Target Deviation (%)” Worksheet Description: Represents the % difference, or error, between the elevation (mamsl) target for the end of each time period and the simulated reservoir elevation at the end of each time period.
- “Active Storage Volume Capacity” Worksheet Description: Represents maximum capacity (m^3) of a system element to store water within its active storage zone during each time period. This value will not remain constant over time in a reservoir if sediment volume accumulates in the reservoir.
- “Act. Stor. Capacity Reduction” Worksheet Description: Represents the percentage (%) reduction in size of the initial capacity of the active storage zone in each reservoir during each time period.
- “Dead Storage Volume Capacity” Worksheet Description: Represents the maximum capacity (m^3) of a reservoir to store water in the dead storage zone during each time period. The value of this variable for a particular reservoir is only different from the initial value if sediment accumulates in the dead storage zone of the reservoir.
- “Dead Stor. Capacity Reduction” Worksheet Description: Represents the percentage (%) reduction in size of the initial capacity of the dead storage zone in each reservoir during each time period.
- “Flow_inflow” Worksheet Description: Represents water discharge (m^3/s) into a reach or reservoir during each time period.
- “Flow_outflow” Worksheet Description: Represents the water discharge (m^3/s) from each element (reaches and reservoirs), not including evaporation.
- “Storage_evaporation” Worksheet Description: Represents water evaporation rate (m^3/s) at each reservoir site during each time period.

- “Downstream Flow” Worksheet Description: Represents water discharge (m^3/s) released from a reservoir during each time period that enters the reach immediately downstream of the reservoir.
- “Turbine Flow” Worksheet Description: Represents water discharge (m^3/s) released from a reservoir during each time period through the hydropower outlet (turbines).
- “Spilled Flow” Worksheet Description: Represents water discharge (m^3/s) released from a reservoir during each time period that does not generate any power.
- “Overflow Worksheet” Description: Represents water discharge (m^3/s) released from a reservoir during each time period through the spillway outlet.
- “Diversion Flow” Worksheet Description: Represents water discharge (m^3/s) released from a reservoir during each time period through the diversion outlet.
- “Controlled Flow” Worksheet Description: Represents water discharge (m^3/s) released from a reservoir during each time period through the controlled outlet.
- “Low level flow” Worksheet Description: Represents water discharge (m^3/s) released from a reservoir during each time period through the low-level flushing outlet.
- “Power Production (MW)” Worksheet Description: Represents the power (MW) generated at a hydropower dam during each time period.
- “Energy Production (MWH)” Worksheet Description: Represents the energy (MWH) generated at a hydropower dam during each time period.
- “Suspended Sediment Mass Inflow” Worksheet Description: Represents the mass of suspended sediment (kg) that enters a system element during one time period.
- “Suspended Sediment Mass Outflow” Worksheet Description: Represents the mass of suspended sediment (kg) that exits a system element during one time period.
- “Trap Efficiency” Worksheet Description: Represents the trap efficiency (as a fraction) for each reservoir in the system during each time period.
- “Residence Time” Worksheet Description: Represents the residence time (years) of water in each reservoir at the end of each time period.
- “Settled Sediment Mass” Worksheet Description: Represents the sediment mass (kg) held in bottom storage in the element of interest at the end of each time period. This value can increase or decrease depending on whether scour or deposition is the dominant process.
- “Suspended Sediment Mass” Worksheet Description: Represents the mass (kg) of sediment in suspension in a reach or reservoir during a time period.
- “Total Sediment Mass” Worksheet Description: This variable represents the sum (kg) of the bottom sediment mass and suspended sediment mass, which are defined in their respective worksheets.
- “Total Sediment Surplus Deficit” Worksheet Description: Represents the total sediment (kg) that exists in a reach or reservoir at the end of each time periodhat is in excess (or deficit) of the amount of sediment that existed in the element at the start of simulation.
- “Flow_Junction” Worksheet Description: Represents the water discharge (m^3/s) at each user-defined junction.
- “Flow_bypass” Worksheet Description: Represents the water discharge (m^3/s) in the reservoir bypass channel.
- “Bypass Suspended Sediment Mass” Worksheet Description: Represents the suspended sediment mass (kg) discharged into the reservoir bypass channel

The following is a more detailed discussion of the model output contained within each of the time series output file worksheets. The worksheet names are listed in bold type.

1. **Water Storage (m^3).** This variable represents the volume of water (m^3) stored at the end of every time period in a reservoir or reach.
2. **Water Surface Elevation (mamsl).** This variable represents the elevation (mamsl) associated with the water storage (m^3) in each reservoir in each time period. This is determined via interpolation over the user-provided Elevation-Volume table. The reported elevation does account for impact of accumulation of sediment volume on the water surface elevation.
3. **Active Storage Volume (m^3).** This variable represents the volume (m^3) of water held within the active storage zone at the end of each time period. This value can vary over time. However, active storage is limited to the active storage capacity, which is given by the volume of water held between the low and full supply level elevations (the elevations between which the reservoir is expected to be operated for hydropower generation). The active storage capacity can also change over time, as will be discussed below.
4. **Dead Storage Volume (m^3).** This variable represents the volume (m^3) of water held within the dead storage zone in each reservoir at the end of each time period. This value can vary over time as the water storage in the reservoir varies (assuming the water level drops below the lower limit of the active storage zone). However, dead storage is limited to the dead storage capacity, which is given by the volume of water held below the low supply level (below the bottom of the active storage).
5. **Storage Volume - Target Deviation (m^3).** This variable represents the difference (m^3) , or deviation, between the user-established reservoir storage volume target (m^3) for the end of each time period and the simulated reservoir storage at the end of each time period. This variable is only applicable to a particular reservoir if the user is simulating hydrology internally in the model and selects the option to operate the reservoir based on storage volume targets (rather than storage elevation targets).
6. **Storage Volume - Target Deviation (%).** This variable represents the error between the user-established reservoir storage target (m^3) for the end of each time period and the simulated reservoir storage at the end of each time period, represented as a % of the storage target. This variable is only applicable to a particular reservoir if the user is simulating hydrology internally in the model and selects the option to operate the reservoir based on storage targets (rather than storage elevation targets).
7. **Elevation Target Deviation (m^3).** This variable represents the difference (m^3) , between the user-established reservoir elevation target (mamsl) for the end of each time period and the simulated reservoir storage elevation at the end of each time period. This variable is only applicable to a particular reservoir if the user is simulating hydrology internally in the model

and selects the option to operate the reservoir based on storage elevation targets (rather than storage volume targets).

8. **Elevation Target Deviation (%).** This variable represents the difference between the user-established reservoir storage elevation target (mamsl) for the end of each time period and the simulated reservoir storage elevation at the end of each time period, represented as a % of the storage elevation target. This variable is only applicable to a particular reservoir if the user is simulating hydrology internally in the model and selects the option to operate the reservoir based on storage elevation targets (rather than storage volume targets).

9. **Active Storage Volume Capacity (m^3).** This variable represents maximum capacity (m^3) of a reservoir to store water within its active storage zone. This value is defined at the simulation start date by the user in the "Reservoir Specifications" worksheet. This value will not remain constant if sediment volume accumulates in the reservoir.

10. **Active Storage Capacity Reduction (%).** This variable represents the percentage reduction in size of the initial capacity of the active storage volume zone in each reservoir. The active capacity will only be reduced in size from the initial value if sedimentation in the active storage volume zone occurs.

11. **Dead Storage Volume Capacity (m^3).** This variable represents maximum capacity (m^3) of a reservoir to store water within its dead storage volume zone. This value is defined for the simulation start date by the user in the "Reservoir Specifications" worksheet. This value will not remain constant if sediment volume accumulates in the reservoir.

12. **Dead Storage Capacity Reduction (%).** This variable represents the percentage reduction in size of the initial capacity of the dead storage zone in each reservoir. The dead capacity will only be reduced in size from the initial value if sedimentation in dead storage zone occurs.

13. **Flow_inflow (m^3/s).** This variable represents the water flow rate (m^3/s) into a reach or reservoir during each time period. The value reported for each time period is assumed to remain constant for the duration of that time period.

14. **Flow_outflow (m^3/s).** This variable represents the water flow rate (m^3/s) out of a reach or reservoir during each time period. The value reported for each time period is assumed to remain constant for the duration of that time period. Note that for reservoirs, this value represents the sum of the discharge from all of the reservoir's outlets during the time period.

15. **Flow_junction (m^3/s).** This variable represents the water flow rate at each user-defined junction during each time period. The value reported for each time period is assumed to remain constant for the duration of that time period.

16. **Suspended sed. mass junction (kg).** This variable represents the suspended sediment mass (kg) entering each user-defined junction during each time period. The value reported for each time period is assumed to remain constant for the duration of that time period.

17. **Storage_evaporation (m^3/s).** This variable represents the water loss from evaporation expressed as a flow rate (m^3/s) for each reservoir during each time period. The value reported for each time period is assumed to remain constant for the duration of that time period.

18. **Downstream flow (m^3/s).** This variable represents the water flow rate (m^3/s) that enters the reach (channel) or reservoir immediately downstream of the reservoir of interest each time period. At diversion reservoirs, this value does not include the diverted flow rate. The value reported for each time period is assumed to remain constant for the duration of that time period. This variable is only reported for hydrologic simulations that are conducted using the *SedSim* model.

19. **Turbine flow (m^3/s).** This variable represents the water flow rate (m^3/s) that is discharged through the turbines of the hydropower plant at the reservoir in each time period. Turbine flow is constrained by the discharge capacity of the outlet works that feed the turbines, and by the maximum power (MW) capacity of the turbines. The value reported for each time period is assumed to remain constant for the duration of that time period. This variable is only reported for hydrologic simulations that are conducted using the *SedSim* model.

20. **Flow_bypass (m^3/s).** This variable represents the water flow rate (m^3/s) that is discharged into every reservoir bypass, if a reservoir bypass exists. The remainder of flow is assumed to enter the reservoir.

21. **Spilled Flow (m^3/s).** This variable represents any water flow rate (m^3/s) that is discharged from the reservoir during each time period without contributing to hydropower production. Any outlet that does not generate hydropower contributes flow to the spill rate. The value reported for each time period is assumed to remain constant for the duration of that time period. This variable is only reported for hydrologic simulations that are conducted using the *SedSim* model. Spill flows include overflows.

22. **Overflow (m^3/s).** This variable represents any water flow rate (m^3/s) that is discharged from the overflow (spillway) outlet of a reservoir each time period, which generally separates the top of the active storage zone from the flood storage zone. The value reported for each time period is assumed to remain constant for the duration of that time period. This variable is only reported for hydrologic simulations that are conducted using the *SedSim* model.

23. **Diversion flow (m^3/s).** This variable represents any water flow rate (m^3/s) that is discharged from the diversion outlet during each time period. The value reported for each time period is assumed to remain constant for the duration of that time period. This variable is only reported for hydrologic simulations that are conducted using the *SedSim* model.

24. **Controlled flow (m^3/s).** This variable represents any water flow rate (m^3/s) that is discharged from the controlled outlet of a reservoir during each time period. The value reported for each time period is assumed to remain constant for the duration of that time period. This variable is only reported for hydrologic simulations that are conducted using the *SedSim* model.

25. **Low level flow (m^3/s).** This variable represents any water flow rate (m^3/s) that is discharged from the low level outlet of a reservoir during each time period. The value reported for each time period is assumed to remain constant for the duration of that time period. This variable is only reported for hydrologic simulations that are conducted using the *SedSim* model.

26. **Power Production (MW).** This variable represents the hydropower production at each reservoir during each time period. The value cannot exceed the user-supplied hydropower plant capacity (in the "Reservoir Specifications" worksheet in the input data file).

27. **Energy Production (MWH).** This variable represents the energy production at each hydropower reservoir during each time period.

28. **Suspended Sediment Mass Inflow (kg).** This variable represents the mass of suspended sediment (kg) that enters a reach or reservoir during each time period.

29. **Suspended Sediment Mass Outflow (kg).** This variable represents the mass of suspended sediment (kg) that exits a reach or reservoir during each time period.

30. **Bypass Suspended Sediment Mass (kg).** This variable represents the suspended sediment mass (kg) contained in the flow that is discharged into each reservoir's sediment bypass, if a sediment bypass exists for the reservoir.

31. **Trapping Efficiency (fraction).** This calculated value is the fraction of suspended sediment that remains in the reservoir in a simulated time period. Available sediment includes sediment that remains in suspension from a previous time period and sediment that enters the reservoir from an upstream element during the time period.

32. **Residence Time (years).** This variable represents the residence time (years) of water in a reservoir. This value currently is currently calculated based on the average storage (m^3) over the last 365 days, and the total reservoir outflow volume during the last 365 days (m^3).

33. **Settled Sediment Mass (kg).** This variable represents the sediment mass (kg) that is held in bottom storage in the element of interest. This includes sediment that has settled in the dead and active storage zones. In reservoirs, the bottom sediment mass includes only mass that has been trapped according to the *Brune* [1953] curve trap efficiency. The user may specify that some bottom sediment mass exists in reservoirs at the beginning of simulation. In reaches, a calibrated rating function such as appears in Eq. (A2.3) is responsible for determining the discharge of sediment from a reach. Any sediment that exists in suspension (either as a remainder from the previous simulation period or as inflow from an upstream reach or reservoir) in excess of the carrying capacity mass and that is not discharged from the reach must settle in the reach. This settled mass contributes to the bottom sediment mass. In reaches, this bottom sediment mass can be re-suspended in future time periods when not enough sediment exists in suspension in a reach to satisfy the sediment mass discharge specified by the calibrated carrying capacity function. Each reach begins with a pre-specified, finite amount of initial sediment mass, and is therefore by definition exhaustible. In

reservoirs, a variety of sediment management practices are capable of removing the settled sediment.

34. **Suspended Sediment Mass (kg).** This variable represents the mass (kg) of sediment in suspension in a reach or reservoir. In reservoirs, suspended sediment mass is any mass that is not trapped due to sedimentation or discharged from the reservoir outlets. The same is true of reaches, in that suspended sediment is sediment that did not settle or get discharged from the reach.

35. **Total Sediment Mass (kg).** This variable represents the sum (kg) of the bottom sediment mass and suspended sediment mass, which were defined previously.

36. **Total Sed. Surplus Deficit (kg).** This variable represents the total sediment mass (kg) that exists in a reach or reservoir that is in excess (or deficit) of the amount of sediment that existed in the element at the beginning of simulation. As reservoirs do not begin with initial sediment mass availability in the bottom sediment mass pool, the the value of this variable is always a surplus value in reservoirs, and is equal to the total sediment mass stored in the reservoir. Conversely, reaches are initialized with a certain amount of sediment mass. For this reason, the TS_surplus_deficit value is useful reach-related information to review, because it indicates what total quantity of mass (including suspended and settled mass) resides in a reach that is different from the value assumed to exist at the simulation start date.

Statistics Output File

The statistics output file contains many more worksheets than the time series output file. They are listed below together with a short description. Many of the worksheets are only slightly different from one another. For this reason, every worksheet contained in this output file will not be separately described. Instead, this section will provide a description of the six different types of statistical manipulation of the time series data that are provided, and a summary of which variables are included within of these six categories. Before the six categories are presented, it will first be helpful to provide a more detailed description of the first two worksheets that appear in this output file (assuming a regulated system simulation):

1. **Power Reliability.** For every reservoir, this worksheet provides the reliability for various levels of hydropower production, where power reliability for a particular level of power production is defined as the fraction of the simulation days during which power production at the reservoir exceeded the power production level of interest. Reliability results for each reservoir are shown for 50 different levels of power production, where each interval is equally sized at 1/50 of the facility's power production capacity (MW).

2. **Energy Reliability.** For every reservoir, this worksheet provides the reliability for various levels of hydropower facility energy production, where energy reliability for a particular level of power production is defined as the fraction of the simulation days during which energy production at the reservoir exceeded the energy production level of interest. Reliability results for each reservoir are shown for 50 different levels of energy production,

where each interval is equally sized at 1/50 of the facility's energy production capacity (MWH).

The following six categories of statistical calculations are applicable to many of the worksheets. For some of the variables, only four of the six categories are applicable, whereas all of the categories apply for a few of the variables. After the categories are presented, a list of the variables to which each category applies is provided.

A. **Annual Statistics.** For every reach and reservoir, this worksheet presents the mean, standard deviation, maximum, minimum, and median of all the daily variable values contained within each year. For example, for a 50 year simulation, for every reservoir the water inflow rate (m^3/s) worksheet would include 50 mean annual flow rates, 50 standard deviations, etc.

B. **Annual Sum Statistics.** For every reach and reservoir, this worksheet presents the annual sum of all the daily variable values contained within each year. For example, for a 50 year simulation, for every reservoir the water inflow volume (m3) worksheet would include 50 annual inflow volume values (one for each simulation year). In this case, the point of the worksheet is to report the annual sum, which means statistics are not relevant. Note that Sum-based manipulations of the time series are not appropriate for all variables. For example, taking the sum of daily inflow rates over the course of one simulation year would not be meaningful information.

C. **Monthly Statistics.** For every reach and reservoir, this worksheet presents the mean, standard deviation, maximum, minimum, and median of all the daily variable values contained within each month. For example, for a 50 year simulation, for every reservoir the water inflow rate (m^3/s) worksheet would include 12*50=600 mean monthly flow rates, 50*12 monthly standard deviations of flow rate, etc.

D. **Monthly Sum Statistics.** For every reach and reservoir, this worksheet presents the monthly sum of all the daily variable values contained within each month. For example, for a 50 year simulation, for every reservoir the water inflow volume (m^3) worksheet would include 12*50 monthly inflow volume values (one for each simulation month). In this case, the point of the worksheet is to report the monthly sum, which means statistics are not relevant. Note that Sum-based manipulations of the time series are not appropriate for all variables. For example, taking the sum of daily inflow rates over the course of one month in a particular simulation year would not be meaningful information.

E. **Mean Monthly Statistics.** For every reach and reservoir, this worksheet presents the mean of the mean, standard deviation, maximum, minimum, and median of all the daily variable values contained within each month. For example, for a 50-year simulation, for every reservoir the water inflow rate (m^3/s) worksheet would include 12 means (each of the 12 taken over the 50 mean monthly flow rates for each month), 12 means of the standard deviations of flow rates, etc.

F. **Mean Monthly Sum Statistics.** For every reach and reservoir, this worksheet presents the mean, standard deviation, maximum, minimum and median of the monthly sum of all the daily variable values contained within each month. For example, for a 50 year simulation, for every reservoir the water inflow volume (m^3) would include 12 (one for each month) mean monthly inflow volume values (taken over the 50 sums), 12 (one for each month) standard deviations of the monthly inflow volume values (taken over the 50 sums), etc. Note that Sum-based manipulations of the time series are not appropriate for all variables. For example, taking the sum of daily inflow rates over the course of one month in a particular simulation year would not be meaningful information.

For categories A, C and E above, variables for which corresponding worksheets are provided are the following:

i. Water Storage
ii. Suspended Sediment Mass
iii. Settled Sediment Mass
iv. Total Sediment Mass
v. Total Sediment Surplus Deficit
vi. Outflow Rate
vii. Inflow Rate
viii. Outflow Volume
ix. Inflow Volume
x. Sediment Mass Outflow
xi. Sediment Mass Inflow
xii. Water Surface Elevation
xiii. Trap Efficiency
xiv. Residence Time
xv. Power
xvi. Energy
xvii. Spilled Flow

For categories B, D and F above, variables for which corresponding worksheets are provided are the following:

vii. Outflow Volume
viii. Inflow Volume
ix. Sediment Mass Outflow
x. Sediment Mass Inflow
xi. Energy

8 Assumptions, Limitations and Caveats

These comments apply to the application of the *SedSim* model to the Mekong Basin:

- Modeling sediment even using 3D hydrodynamic models is a difficult task. Hydraulic studies in laboratories typically are based on a much more detailed knowledge of the distribution of sediment sizes, densities, and even sediment shapes. Thus to think that these daily simulations using a 1D mass balance model are in some sense accurate would be a mistake. We view this *SedSim* model as strictly a screening tool, and even then the focus should be on the relative changes in sediment loads and depositions rather than the actual ones. In addition averages of these daily results over longer time periods are probably more reliable than the daily results themselves.

- The way sediment is currently modeled does not distinguish between suspended and bed loads, or among different sediment size classes. Once data availability justifies the distinction between bed and suspended loads, the accuracy of the predicted sediment load simulations could be improved.

- The main purpose of this modeling exercise is to assess the impact of changes in the hydrologic and sediment regimes on the ecosystems in the basin, especially in the Tonle Sap and Delta regions. We need to be aware of the uncertainties of such predictions even assuming our hydrologic and sediment inputs are without errors, and not waste time and resources perfecting our sediment predictions if the added precision does not improve the accuracy of the ecological predictions.

9 References

Atkinson, E. (1996), *The Feasibility of Flushing Sediment from Reservoirs,* TDR Project R5839, Rep OD 137, HR Wallingford.

Annandale, G.W. (2013), *Quenching the Thirst: Sustainable Water Supply and Climate Change,* CreateSpace, North Charleston, S. C.

Brune, G.M. (1953), Trap Efficiency of Reservoirs, *Trans. AGU*, 34, 407-418.

Churchill, M.A. (1948), Discussion of paper by L.C. Gottschalk, Analysis of Use of Reservoir Sedimentation Data, in *Proceedings of the Federal Inter-Agency Sedimentation Conference*, Denver, CO, 139-140.

Fan, J. (1986), Turbid Density Currents in Reservoirs, *Water International*, 11 (3): 107-116.

Fan, J. (1991), Density Currents in Reservoirs, *Workshop on Management of Reservoir Sedimentation*, New Delhi.

Gupta, A., and S.C. Liew (2007), The Mekong from satellite imagery: a quick look at a large river, *Geomorphology*, 85, 259-274.

ICEM, 2010, *MRC Strategic Environmental Assessment (SEA) of hydropower on the Mekong Mainstream*, Hanoi, Viet Nam.

Kawashima, S., T.B. Johndrow, G.W. Annandale, and F. Shah (2003), *Reservoir conservation volume I: the RESCON approach, economic and engineering evaluation of alternative strategies for managing sedimentation in storage reservoirs, A contribution to promote* *conservation of water storage assets worldwide*, The International Bank for Reconstruction and Development /The World Bank, Washington, DC, USA, 52.

Kondolf, G.M. (1997), Hungry water: Effects of dams and gravel mining on river channels, *Environ. Manage.*, 21(4), 533-551.

Kondolf, G.M., C. Alford, and Z. Rubin (2011), *Cumulative Effects of Tributary Dams on the Sediment Loads and Channel Form in the Lower Mekong River: Progress Report through 30 September 2011*, Dep. of Landscape Archit. and Environ. Plann., Univ. of California, Berkeley.

Kummu, M., and O. Varis (2007), Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River, *Geomorphology*, 85, 275-293.

Kummu, M., X.X. Lu, J.J. Wang, and O. Varis (2010), Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong, *Geomorphology*, 119, 181–197.

Mekong River Commission (MRC) (2005), *Overview of the Hydrology of the Mekong Basin*, Mekong River Comm., Vientiane, November 2005, 73.

Mekong River Commission (MRC) (2009), Modelling the cumulative barrier and passage effects of mainstream hydropower dams on migratory fish populations in the Lower Mekong Basin, *MRC Technical Paper No. 25*, Mekong River Comm., Vientiane, 2009.

Mekong River Commission (MRC) (2010), *State of the Basin Report*, Mekong River Comm., Vientiane, 2010.

Mekong River Commission (MRC) (2012), Hydropower Project Database, Basin Development Plan Programme, Mekong River Comm., Vientiane, Lao PDR.

Meybeck, M., L. Laroche, H.H. Durr, and J.P.M. Syvitski J.P.M. (2003), Global variability of daily total suspended solids and their fluxes in rivers, *Global Planet. Change* 39(1-2): 65-93.

Migniot, C. (1981), Erosion and Sedimentation in sea and river, *La Pratique des sols et des fondations*, editions Le Moniteur 1981.

Milliman, J.D., and R.H. Meade (1983), World-wide delivery of river sediment to the oceans, *Geology*, 91, 1-21.

Morehead, M.D., J.P. Syvitski, E.W.H. Hutton, and S.D. Peckham (2003), Modeling the temporal variability in the flux of sediment from ungaged river basins, *Global Planet. Change*, 39(1-2), 95-110.

Morris, G.L., and J. Fan (1998), *Reservoir Sedimentation Handbook*, McGraw Hill, New York.

Palmieri A., F. Shah, G.W. Annandale, and A. Dinar (2003), *Reservoir Conservation Volume I: the RESCON Approach, economic and engineering evaluation of alternative strategies for managing sedimentation in storage reservoirs, A contribution to promote conservation of water storage assets worldwide*, Int. Bank for Reconstruction and Dev./The World Bank, Washington, D.C., 101.

Strand, R. I., and E.L. Pemberton (1987), Reservoir Sedimentation, In *Design of Small Dams*, U.S. Bureau of Reclamation, Denver, CO.

Vörösmarty, C.J., M. Meybeck, B. Fekete, K. Sharma, P. Green, and J.P.M. Syvitski (2003), Anthropogenic sediment retention: major global impact from registered river impoundments, *Global Planet. Change*, 39(1–2), 169–190.

Walling, D.E., and B.W. Webb (1983), Patterns of Sediment Yield, in *Background to Pelaeohydrology*, edited by K.J. Gregory, pp. 69-100, Wiley, New York, NY.

Walling, D. (2005), *Analysis and evaluation of sediment data from the Lower Mekong River, Report submitted to the Mekong River Commission*, Department of Geography, University of Exeter.

Walling, D.E. (2009), The Sediment Load of the Mekong River, in *The Mekong: Biophysical Environment of an International River Basin*, edited by I.C. Campbell, pp.113-142, Elsevier, Amsterdam.

Wang, G. Q., B. S. Wu, and Z.-Y. Wang (2005), Sedimentation problems and management strategies of Sanmenxia reservoir, Yellow River, China, *Water Resour. Res.*, 41, W09417, doi:10.1029/2004WR003919.

Wang, J.J., X.X. Lu, and M. Kummu (2011), Sediment load estimates and variations in the Lower Mekong River, *Riv. Res. Appl.*, 27, 33-46.

Washburn, E.W. (1928), *International Critical Tables of Numerical Data, Physics, Chemistry and Technology*, National Research Council of USA, McGraw-Hill, New York.

White, W.R. (2000), Flushing of Sediments From Reservoirs, *Thematic Review IV.5*, World Commission on Dams.

White, W. R. (2001), *Evacuation of Sediments from Reservoirs*, Thomas Telford, London.

Xue, Z., J.P. Liu, D. DeMaster, L.V. Nguyen, and T.K.O Ta (2010), Late Holocene Evolution of the Mekong Subaqueous Delta, Southern Vietnam, *Mar. Geol.*, 269, 45-60.

10 Access to Model Software

When in the main model workbook, simultaneously pressing the Alt and F11 keys (Alt-F11) will open up the windows that allow access to the visual basic application software that executes the *SedSim* model. This will open the Microsoft Visual Basic editor. Next, double-click on the category titled "VBAProject (SedSim.xlsm)". You will then be required to enter the password you have been given to access the model's source code. Next, click on the "Modules" folder, and double click on "SedimentModel". If you wish to close the visual basic editor and return to the *SedSim* model interface, press Alt-F11 again. As long as you keep the “SedSim.xlsm” file open, you can continue to access the source code you have already opened without needing to enter a password every time. The authors of this program suggest saving the model as it is before making any changes, in case those changes do not perform as expected. We are not going to be able to debug different versions of this program, and would rather have users send us suggestions on what might be changed or added and we can try to do that.

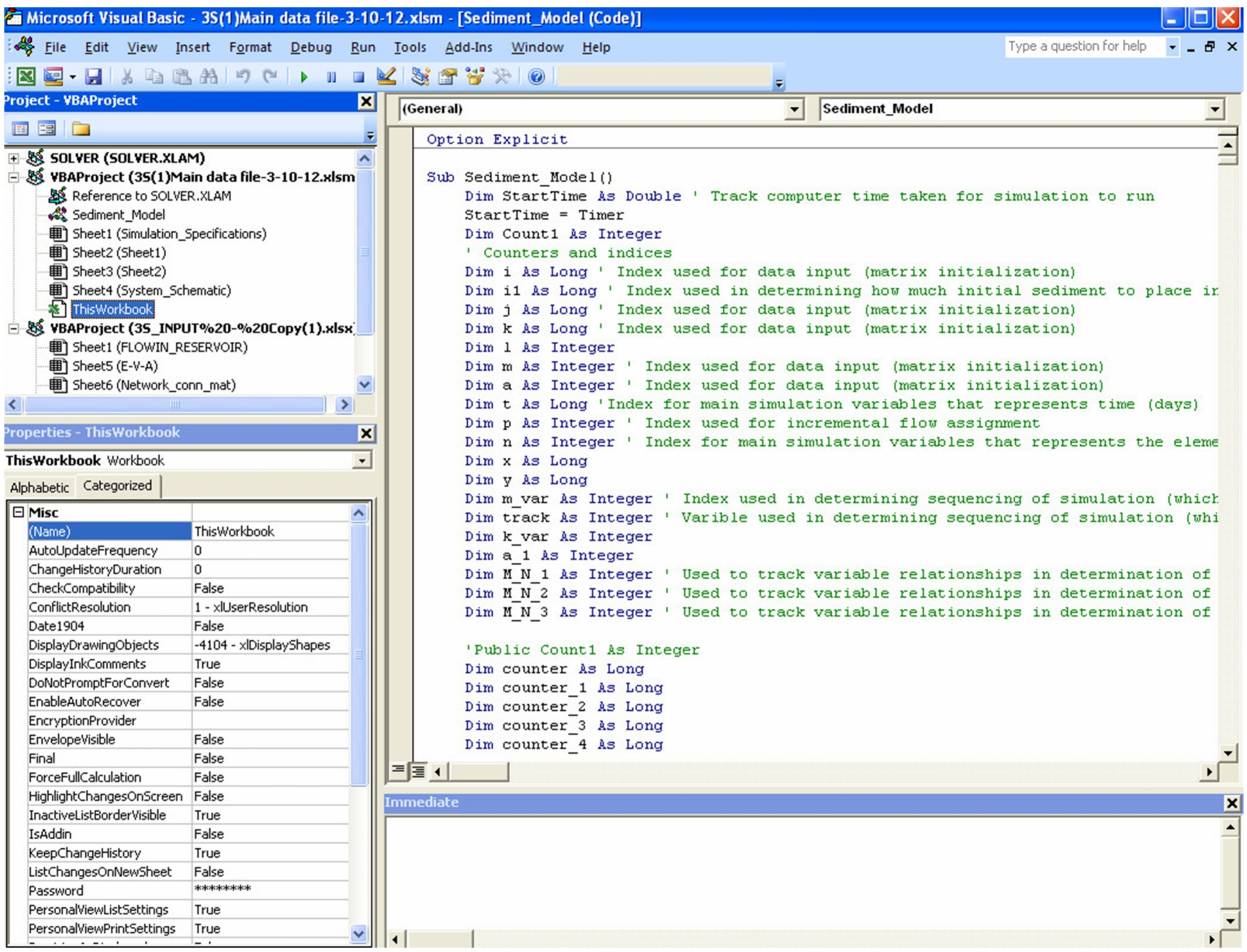


Figure A10.1. A display of the beginning of the *SedSim* program VBA code resulting from selecting Alt + F11 when the main model workbook is open.

11 *SedSim* Simulation Equations for Flow, Sediment and Hydropower

SedSim simulates the mass balance of water and sediment in each reach (or river channel) and reservoir, as well as the hydropower production associated with the water released during each time period.

For reaches and reservoirs, the inflows of water and sediment mass are determined in the same way, by summing all of the inflows into the reach or reservoir of interest. In symbolic form, the water and sediment mass balances are given by the following:

Water:

IQ(j,t) = Incremental inflow (m^3/s) to reach j in period t

Qin(j,t) = total inflow (m^3/s) from upstream reaches and/or reservoirs, diversions, and incremental inflow into reservoir j in period t.

= Σ outflow over all incoming reaches k to reach j + Σ outflow over all incoming reservoirs z to reach j + Σ over all incoming diversions d to reach j + Σ incremental inflows into reach j

$= \sum_k \mathrm{Q}_o \quad (\mathrm{k,t}) + \sum_z \mathrm{Q}_o \quad (\mathrm{z,t}) + \sum_d \mathrm{Q}_o \quad (\mathrm{d,t}) + \mathrm{IQ(j,t)}$

Sediment:

IS(j,t) = Incremental mass (kg) of sediment to reach j in period t

SMin(j,t) = total inflow (kg) from upstream reaches and/or reservoirs, diversions, and incremental inflow into reservoir j in period t.

= Σ outflow over all incoming reaches k to reach j + Σ outflow over all incoming reservoirs z to reach j + Σ over all incoming diversions d to reach j + Σ incremental inflows into reach j

$= \sum_k \mathrm{SM}_o \quad (\mathrm{k,t}) + \sum_z \mathrm{SM}_o \quad (\mathrm{z,t}) + \sum_d \mathrm{SM}_o \quad (\mathrm{d,t}) + \mathrm{IS(j,t)}$

Next, assumptions specific to reaches and reservoirs are discussed, respectively.

Reach components

Water

Internal hydrologic simulation requires river reach flow routing. Note that sediment simulation and flow simulation in reaches are completely separated in *SedSim*, in that the extent of deposition/scour/concentration does not impact flow. Each reach is assumed to be similar to a lake in which the outflow is a function of the storage (elevation) in the reach. In the *SedSim* model the release of water from each reach in each time period is assumed to be defined as a non-linear function of the total initial storage volume plus inflow minus losses in each period minus the volume that would remain in ponds in the reach if all remaining water were suddenly withdrawn. Letting S(t) be the initial storage volume (m^3); I(t) the inflow volume; L(t) the losses from seepage and evaporation; and PS the ponding storage, or the reach storage volume below which no outflow occurs; the outflow $Q_{out}(t)$ (m^3/s) in period t will be

$$Q_{out}(t) = \delta[S(t) - \min(PS, S(t)) + I(t) - L(t)]^{\gamma} \text{for all periods t}$$

Parameters PS, δ and γ will differ for each reach. Both δ and γ will usually be less than 1 but never outside the range from 0 to 1. If the value of the expression in brackets is less than 1, then γ is assumed to be 1.

The final reach storage volume is:

$$S(t+1) = S(t) + I(t) - L(t) - Q_{out}(t)\Delta t \qquad \text{for all periods t}$$

Alternatively, the user can choose to specify that reach outflow equals reach inflow (steady state).

Sediment

SM(j,t) = mass of sediment in reach j at beginning of period t

$SM_{out}(k,t)$ = sediment mass (kg) outflow from reach k in period t
= Min{a(j) * $Q_{out}(j,t)^{b(j)}$ * $Q_{out}(j,t)$ * Δt, Sediment available in reach as bed or suspended sediment}

where a(j) and b(j) are user-defined sediment carrying capacity constants for reach j.

$$SM(j,t) + SM_{in}(j,t) - SM_{out}(j,t) = SM(j,t+1)$$

<u>Reservoir components</u>

Flows:

The outflow rate (m^3/s) from reservoir j in time period t, $Q_{out}(j,t)$, is given by the following relationship:

$$Qout(j,t) = \text{Min}\{\text{Max}\{R_{ST}(j,t), R_{Env}(j,t)\}, K_R(j,t), \text{Max}\{0, (S(j,t) + V_{in}(j,t) - Evap(j,t) * \Delta t)/ \Delta t\}\}$$

where $R_{ST}(j,t)$ is the water release rate (m^3/s) required to meet the storage target (m^3) at reservoir j at the end of time period t (or beginning of time period t+1); $R_{Env}(j,t)$ is the user-established minimum downstream environmental flow (m^3/s) for reservoir j during time period t; $K_R(j,t)$ is the capacity (m^3/s) of the outlets at reservoir j to release flow during time period t; and $V_{in}(j,t)$ is the water inflow volume (m^3) to reservoir j during time period t; S(j,t) is the water storage volume (m^3) at reservoir j at the beginning of time period t; and Evap(j,t) is the evaporation rate (m^3/s) from reservoir j during time period t.

The storage target, $S_{Target}(j,t)$, represents the storage target (m^3) in reservoir j to be met at the end of period t (i.e., the storage target for the beginning of period t+1). This can be the user's pre-established storage target for the current date, the storage target corresponding to the user's pre-established water surface elevation target, or a storage target that is established internally in *SedSim* to achieve sediment management-related goals (e.g. to initiate reservoir drawdown for flushing).

Note that $R_{ST}(j,t)$ is defined as follows:

$$R_{ST}(j,t) = S(j,t) + (Q_{in}(j,t) - Evap(j,t)) - V_{S_t}^{S}(j,t) - S_{Target}(j,t)$$

where $V_{S_t}^{S}(j,t)$ is the volume of sediment that settles, or is trapped, in reservoir j during time period *t*. Note that the inflowing water volume (m^3) in a time period is reduced by an amount equal to the volume of sediment that settles, as *SedSim* assumes the estimation of water volume flowing into the reservoir included suspended sediment in the estimation. Any sediment volume that remains in suspension is technically part of the water volume until it settles.

Evaporation (m^3/s), or Evap(j,t), is given by the following relationship:

$$Evap(j,t) = (E_m(j)/D_m)A_s(j,t)/86400$$

where $E_m(j)$ is the average monthly (for the corresponding month time period *t* is in) evaporation depth (mm) at reservoir j; $D_m(j)$ is the number of days in the month time period *t* is in; and $A_s(j,t)$ is the water surface area of reservoir *j* during time period *t*.

The water storage balance is given by the following:

$$S(j,t) + (Q_{in}(j,t) - Qout(j,t) - Evap(j,t)) * \Delta t - V_{S_t}^{S}(j,t)/86400 = S(j,t+1)$$

Every reservoir j begins with an initial total storage capacity, K(j), but this capacity declines as a result of sediment accumulation. That is, the reservoir water storage capacity at the end of each timer period, K(j,t+1), is given by the following:

$$K(j,t+1) = K(j,t) - SSM(j,t+1)/\rho$$

Where SSM(j,t+1) is the mass of sediment that has settled in the reservoir through the end of time period t, and ρ is the user-defined density of deposited sediment (kg/m^3). *SSM* can increase as sediment settles in the reservoir, but can decrease if sediment is removed from the reservoir via sediment management techniques.

Sediment

Under normal operating conditions, the sediment released from a reservoir is given by the following

$SM_{out}(k,t)$ = sediment mass outflow from reach k in period t
$= Q_{out}(j,t)*C(j,t) + S_{rem}(j,t)$

Where $Q_{out}(j,t)$ is the outflow from reservoir j during time period t; C(j,t) is the concentration of sediment stored in suspension in the reservoir j during time period t, assumed to be uniform throughout the reservoir's storage space; and $S_{rem}(j,t)$ is the sediment mass (kg) removed from reservoir j during time period t via flushing or general sediment removal.

The mass of sediment that has settled in the reservoir through the end of time period t, SSM(j,t+1) is described by the following relationship:

$$SSM(j,t+1) = SSM(j,t) + TE(j,t) * SM_{in}(j,t) - S_{rem}(j,t)$$

where TE(j,t) = trapping efficiency of reservoir j in period t based on initial conditions, and $SM_{in}(j,t)$ is the sediment mass (kg) inflow to reservoir j during time period t.

Hydropower

HP(j,t) = Hydropower production (MW) at reservoir j in period t

$= (9.81/1000) * e(j) * h(j,t) * Q_{out}(j,t)$

where h(t,j) is the head above the turbines at reservoir *j* in timer period *t*, and e(j) is the efficiency (fraction) of the turbines at reservoir j, assumed not to vary over time.

The hydropower calculations assume there are no losses in water quantity or in hydraulic head as the water is transmitted from the reservoir to the powerhouse.